European Transport Research Review

ORIGINAL PAPER

Open Access

Modelling interrelations between C-ITS impact categories: a system-dynamics approach using causal loop diagrams

Manuel Walch[1*], Matthias Neubauer[1], Wolfgang Schildorfer[1] and Alexander Schirrer[2]

Abstract

The growing number of connected vehicles has led to an increased focus on Vehicle-to-Everything (V2X) communication in the field of transport research. This communication paradigm facilitates cooperation between vehicles and infrastructure to address traffic challenges such as efficiency, sustainability and safety. The development and standardisation of such Cooperative Intelligent Transport Systems (C-ITS) has been pursued in several projects. Beyond technical considerations, assessing the effect of these applications in terms of various impact categories is of paramount importance. However, existing research tends to examine impact categories such as efficiency, sustainability, safety, psychological or socioeconomic impacts separately, often overlooking potential interactions and interdependencies. This approach is inadequate as impacts on one category can have both cascading effects on others and rebound effects. To address this gap, this paper proposes a system dynamics approach using Causal Loop Diagrams (CLD) to illustrate the interconnectedness of impact categories and the potential impacts of C-ITS services. By depicting general relationships, interdependencies and feedback loops between impact category elements, the model accommodates the introduction of single or multiple C-ITS services as separate modules, allowing an analysis of their combined effects on the overall system. To this end, two use cases demonstrate the applicability of the developed CLD and illustrate some of the multiple interrelations between the effects of C-ITS services. The results of this paper support road operators and researchers when setting up the impact assessment of C-ITS services by revealing the dynamic and intertwined nature of different impact categories.

Keywords Cooperative intelligent transport system, C-ITS, CCAM, Impact assessment, System-dynamics, Causal loop diagram

1 Introduction

In recent years, the integration of advanced sensors and Information and Communication Technology (ICT) capabilities in cars has led to the proliferation of connected vehicles, facilitating data collection and communication between traffic entities (e.g. vehicles, infrastructure elements, pedestrians) [1]. It is estimated that the number of connected vehicles in Europe will exceed 100 million by the end of 2023, which represents a great opportunity for the use of these technologies to address various traffic-related challenges [2, 3]. For example, the growing number of vehicles on the road has led to increased congestion, longer travel times and higher emissions, making road transport the largest contributor to global greenhouse gas emissions [4, 5]. In addition, road safety remains a major concern. Accidents can result not only in financial losses, but also in serious or fatal injuries [6]. In response to these challenges, Cooperative Intelligent Transportation Systems

*Correspondence:
Manuel Walch
manuel.walch@fh-steyr.at
[1] University of Applied Sciences Upper Austria, Wehrgrabengasse 1-3, 4400 Steyr, Austria
[2] Technical University Vienna, Getreidemarkt 9/BA, 1060 Vienna, Austria

(C-ITS) have emerged as a promising solution. They harness the potential of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communication, providing services that are expected to improve the traffic system and promote aspects such as sustainability and safety [3].

The growing importance of V2X (Vehicle-to-Everything) communication has resulted in the definition of several services (e.g. Road-Works-Warning, Hazardous-Location-Notification) within various initiatives (e.g. C-Roads, Car2Car-Communication Consortium) [7–14]. The integration of such C-ITS services into the traffic system has the potential to improve traffic management, foster sustainable mobility solutions, and significantly enhance road safety [3, 15].

However, a deployment of C-ITS requires a prior comprehensive impact assessment to evaluate not only their functionality but also their expected effects to support taking informed (investment) decisions. Impact assessment refers to the process of identifying the future consequences of a current or planned action, such as the introduction of a specific C-ITS service, on various impact categories. These impact categories encompass the effects that are subject to assessment and intend to reflect the essential characteristics of the subject under consideration [16]. In the field of Intelligent Transportation Systems (ITS), crucial impact categories include traffic efficiency, safety, and sustainability [3, 15]. However, based on a comprehensive literature review it can be derived that prevailing research endeavors primarily focus on these impact categories in isolation, overlooking potential interactions, follow-up impacts and rebound effects [17]. Merely [18] propose a high-level evaluation framework for analysing both the direct and indirect effects of automation in road transport. Additionally, [19] present workshop results and subsequent efforts towards developing a high-level consensus framework for understanding the impacts of automated vehicle deployment. However, the current body of literature lacks a thorough examination of the interrelationships, follow-up effects, and rebound effects of impact variables related to C-ITS across different impact categories. Thereby, follow-up or consequential effects refer to subsequent or secondary consequences that occur as a result of an action, leading to positive or negative changes in other areas of a system. In contrast, rebound effects refer to a situation where efforts to increase certain aspects of a system lead to unintended consequences, partially or fully offsetting the intended gains. For impact assessment of C-ITS, it is imperative to consider traffic as a dynamic system which not only has straightforward unidirectional effects, but also consequential and rebound effects.

For instance, while improving road safety through C-ITS might directly lead to a reduction in accidents, it can also have indirect impacts on traffic efficiency. Fewer accidents and smoother traffic flow resulting from enhanced road safety measures can alleviate congestion and reduce delays. Similarly, addressing traffic efficiency can contribute to sustainability goals by decreasing travel times, minimizing stop-and-go traffic, and reducing fuel consumption, ultimately leading to a decrease in emissions. However, traffic efficiency is twofold, as increased traffic efficiency can also attract more traffic or allow higher speeds, leading to higher fuel consumption and emissions. Therefore, acknowledging and understanding the intricate relationships between different impact categories is essential for maximizing the benefits of C-ITS and achieving a safer, more efficient, and sustainable future for transportation.

To bridge this knowledge gap and provide an understanding of the multifaceted impacts of C-ITS, this study aims at an in-depth analysis of various impact categories and their interrelations. As a result, this work aids researchers in the preparation of detailed impact assessment studies by incorporating the potential impact propagation and rebound effects depicted in the Causal Loop Diagram (CLD), and identifying relevant aspects for analysis in advance. Regarding the result representation and application, the following research questions will be addressed:

> *RQ1: How can the impact of C-ITS services, including the interrelations, follow-up effects and rebound effects of single or multiple C-ITS services, be modelled using a system dynamics approach?*

> *RQ2: How can the developed Causal Loop Diagram be applied to reveal the interrelations between impact categories of C-ITS services in specific use cases?*

This document is structured as follows. Section 2 describes the methodology and process used to build the system model. Section 3.1 describes the step-by-step development of a CLD, which illustrates the interdependencies, follow-up effects and rebound effects of the C-ITS impact categories, with the final CLD being illustrated in Sect. 3.2 (see RQ1). Based on the developed system model, Sect. 3.3 introduces C-ITS services and service bundles to illustrate the potential of the developed model for qualitative C-ITS impact assessment (see RQ2). Section 4 closes with concluding remarks.

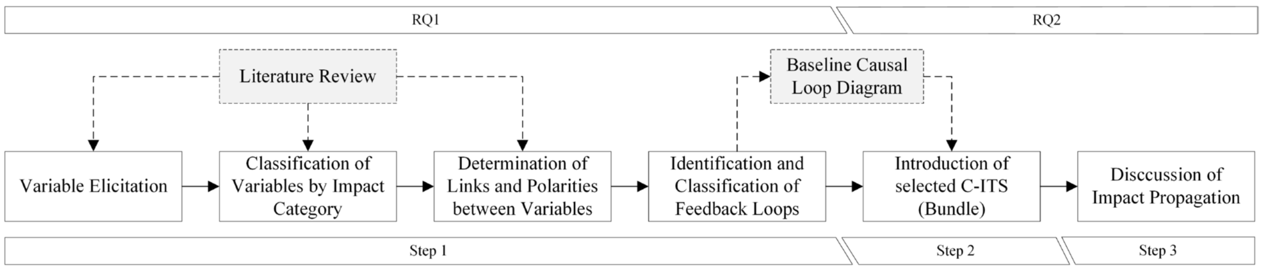

Fig. 1 Methodology

2 Methodology

In this work, the methodology of CLDs was used to investigate the interdependencies between C-ITS impact categories. CLDs are graphical tools for representing, analysing, and comprehending system dynamics. They visually depict system variables interconnected by arrows, denoting cause-and-effect relationships along with the polarities (±) between variables, and identify feedback loops that either reinforce or stabilise system behavior [20]. Their visual representation enhances understanding of intricate dynamics within a system, capturing feedback loops and interconnected elements, thereby fostering a holistic comprehension. Notably, these diagrams contribute to effective communication, and to facilitate shared understanding among stakeholders. Furthermore, they aid decision-making processes by enabling users to visualise potential consequences of interventions and policies while considering the dynamic nature of a system. Nevertheless, it is crucial to acknowledge potential risks, such as oversimplification, as CLDs may not fully encapsulate the complexities of real-world systems. The subjectivity involved in identifying causal relationships introduces the possibility of bias, and the static nature of CLDs may restrict their accuracy in reflecting real-time dynamics. Additionally, CLDs exhibit limited predictive power, prioritizing qualitative aspects of relationships rather than precise forecasting of specific outcomes [21].

In sum, CLDs are a suitable method to visually represent complex causal relationships, facilitating a comprehensive understanding of system dynamics and effectively highlighting potential areas of impact and feedback loops for focused analysis. Therefore, in this paper, CLDs are used to model the impact propagation of C-ITS and to visualise potential feedback effects. Thereby, the developed CLDs can be used not only to analyse the impact propagation of one specific C-ITS service, but to examine different services as well as combinations of services. In this endeavor, the following steps were taken (for the detailed methodological procedure see Fig. 1):

1. Development of a system model in the form of a CLD that illustrates the potential impact variables of C-ITS as well as their system dynamics (reciprocities, consequential effects, rebound effects).
2. Introduction of single or multiple C-ITS services as interchangeable modules and determination of their primary connections on the system model's variables (direct impact on variables).
3. Discussion of impact propagation of the introduced C-ITS services on the modelled overall system, taking into account follow-up and rebound effects.

The basis of this work is a literature review on C-ITS impact assessment, based on which a list of potential variables was created and classified by impact category [17]. Similarly, the links and polarities between variables were defined based on the literature. Intermediate results were periodically discussed and validated through discussions with four additional domain experts to address model bias. After identifying the resulting feedback loops, the baseline CLD was finalised (see Sects. 3.1 and 3.2). This can then be used to analyse the impact propagation of different C-ITS services by introducing them into the system model and defining the connections to relevant variables (see Sect. 3.3).

While the first step is performed only once to create the CLD (apart from possible future extensions), step two and three can be applied as often as required. Due to the high generality of the modelled system, C-ITS services can be inserted or replaced in the CLD in a modular way.

3 Results and discussion

3.1 Development of the baseline causal loop diagram

In this section, the development process of the CLD is outlined. The objective was to establish a general model representing the traffic system, encompassing related consequences, such as follow-up effects and rebound effects. This endeavor is particularly oriented towards its

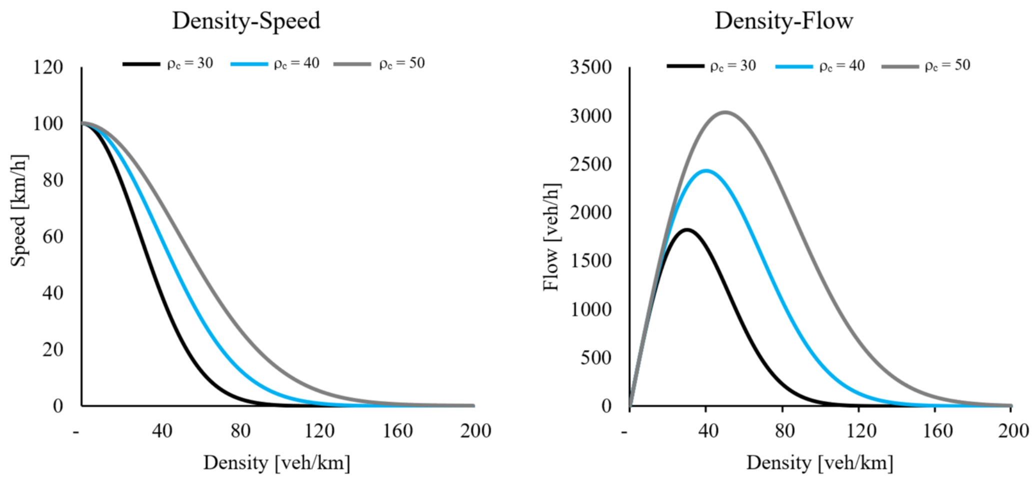

Fig. 2 Drake Fundamental Diagram [24]

applicability in assessing various C-ITS services and their combinations. The foundation for this development relies on the list of variables categorised by their impact (see Appendix 6), which is based on a comprehensive literature review [17]. However, the investigation of interdependencies amid the distinct impact categories requires a preliminary modeling of traffic behaviour itself. This is imperative, since changes in the variables of individual categories arise (in)directly from shifts in traffic behaviour. Hence, the relationship of traffic flow, speed, and density (represented as the fundamental diagram) serves as the basis for the CLD development.

Fundamental diagram of traffic flow

There are various methods of explaining speed-density relationships in traffic flow theory literature [22]. Speed can generally be described as a function of free flow speed and density. For example, in Greenshield's equation [23], this is described as

$$v = v_0 - c\rho \quad (1)$$

where v indicates the velocity, v_0 represents the freeflow speed (desired speed) and ρ indicates traffic density. The variable c in Greenshield's equation is a constant, representing the velocity decrease per density increase (difference ratio).

Greenshield's equation describes the relation between traffic speed and density as a linear function. Another, nonlinear approach was described in Drake's Fundamental Diagram [24].

$$v = v_0 e^{-\frac{1}{2}(\frac{\rho}{\rho_c})^2} \quad (2)$$

In Eq. 2 there is an additional variable ρ_c, indicating the critical density (density with the highest possible traffic flow).

Furthermore, traffic flow can be derived from speed and density, using

$$q = \rho v \quad (3)$$

Based on Eq. 3, one would infer that q increases with both increasing ρ and v. However, since ρ is also a variable influencing v a change in ρ not only directly, but also indirectly influences q via v. This becomes evident when Eq. 2 is inserted into Eq. 3, leading to

$$q = \rho v_0 e^{-\frac{1}{2}(\frac{\rho}{\rho_c})^2} \quad (4)$$

An example of the resulting behaviour can be observed in Fig. 2.

According to the considerations in the fundamental diagram, the speed is dependent on the critical traffic density and the desired speed. The higher both values are, the higher speeds can be achieved. At the same time, a change in traffic density leads to a change in speed. Both, higher speeds and higher traffic densities lead to a higher traffic flow. However, the additional dependence of speed on traffic density leads to a saturation point at the critical traffic density (see Fig. 2). Furthermore, as traffic density is measured as the number of vehicles per unit space, it can be inferred that an increase in traffic volume, assuming unchanged space, leads to an increase in density. Considering the relationships described, the CLD as illustrated in Fig. 3 can be derived.

Based on this model, the other variables of different impact categories were included in the CLD.

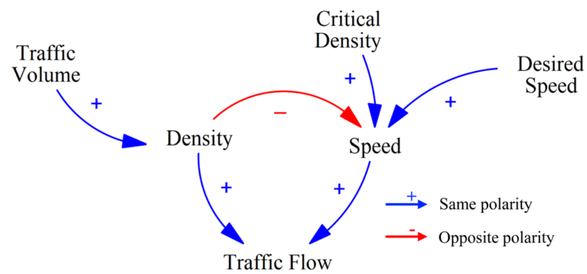

Fig. 3 CLD - Fundamental Diagram

Traffic efficiency

In addition to the variables associated with the fundamental diagram, there are other aspects in the area of traffic efficiency that influence traffic behaviour. For example, the free-flow speed (desired speed) is influenced by the given speed limit, the general tendency of the driver to exceed said speed limit, and by physical limits (e.g. curve radius, gradient, engine power, vehicle mass, weather and road conditions) [25]. Higher speeds result in shorter travel times, while lower speeds lengthen the duration of travel, assuming constant travel distances. Consequently, speeds lower than the freeflow speed and thus longer travel times are associated with delays.

Additionally, longer delays often prompt drivers to consider alternative routes (i.e. choosing a different route option to get from A to B or consolidating activities to avoid additional trips) to bypass congestion and minimise delays. Furthermore, as delay increases, the appeal of public transport options grows. Consequently, there is a positive correlation between travel time, delay and both the number of alternative routes taken and the attractiveness of public transport. If public transport becomes more attractive and more alternative routes are chosen, the volume of traffic decreases or - depending on the trend of traffic volume development - increases slower (e.g. if traffic growth is faster than traffic shift) [26–28] (see B2/3 in Fig. 4).

With higher traffic density, the number of stop-and-go movements also tends to rise [29]. This indicates that as traffic becomes more congested and vehicles experience frequent stops and starts, the occurrence of acceleration and deceleration maneuvers intensifies [30].

However, a greater frequency of speed adaptions adversely affects speed homogeneity [31]. When vehicles on the road frequently accelerate or brake, the uniformity of speeds among vehicles diminishes. Conversely, decreased speed homogeneity again leads to a higher need for speed adaptions [31] (see R1 in Fig. 4). High speed variations also lead to greater strengh of acceleration and deceleration, which is necessary to compensate for the speed differences, and avoid critical situations. In turn, however, heavy acceleration and braking can generate shock waves in traffic, reducing the homogeneity of speed [25, 32] (see R2 in Fig. 4). Moreover, when vehicles of different types dominate the traffic mix, the uniformity of speeds is reduced (in case the given speed limit is not far from the maximum attainable or allowed speed of the vehicle types in place) [33, 34]. Low speed homogeneity also exerts an influence on the number of lane changes, as vehicles moving at different speeds are more likely to switch lanes [33].

Psychological impact

Both number and strength of accelerations and decelerations can be reduced by an increase in driver anticipation, as predicting road conditions and driving with foresight leads to smoother driving patterns [29].

Furthermore, errors in predicting the outcomes of actions may lead to lower speed homogeneity, and therefore to a need for maneuvers to compensate for perceived discrepancies. Similarly, action execution errors are inversely linked to the speed homogeneity, as mistakes during the execution of intended actions fosters variations in traffic speed, resulting in a need for further or stronger velocity adaptions. Moreover, errors in accurately perceiving distances lead to higher speed variations [29].

The reaction time is also an influential factor that affects the uniformity of speed, as the more time it takes to react to a situation, the greater the difference in speed between vehicles [25, 35, 36]. Reaction time is again influenced by further variables. For example, the technical response time has an effect on reaction time, as quicker technological responses can shorten the time taken by drivers to initiate a maneuver [25]. Moreover, action time and mental processing time influence reaction time, with the latter being again influenced by the sensation time, perception time, situation awareness time and decision time [25, 37]. Furthermore, adverse weather conditions (e.g. precipitation) can affect drivers' sensation time by reducing visibility, leading to increased sensory load and potentially slower response to stimuli [38, 39].

Additionally, when drivers are more alert, their cognitive and physiological responses improve, resulting in shorter reaction times and subsequently improving speed homogeneity [40].

Figure 5 illustrates the described interrelations in the form of a CLD and also depicts interrelations with external variables of other categories.

Traffic safety

Psychological impact variables also influence aspects in the area of traffic safety. For example, the reaction time of drivers directly affects their reaction distance. Similarly, higher speeds result in longer distances needed to

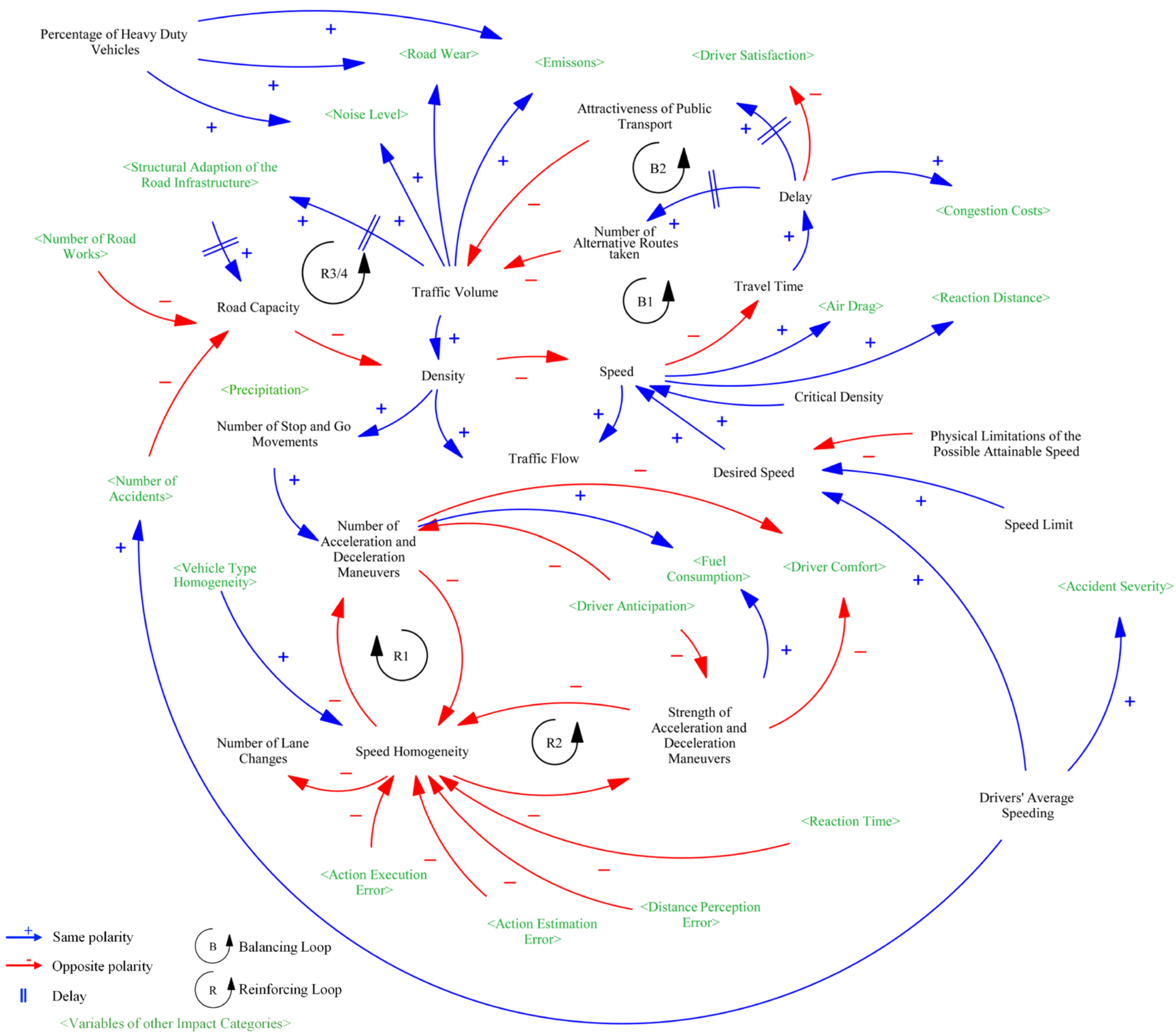

Fig. 4 CLD - Traffic Efficiency

respond to a situation [25]. Furthermore, reaction distance contributes to determining the minimum safety distance between vehicles, as longer distances require a larger safety buffer to ensure sufficient space for braking and preventing collisions. Therefore, it can be inferred that a larger reaction distance translates to a larger minimum safety distance [25].

Furthermore, driver alertness affects various safety related issues, such as driving errors (number of edge-line crossings, frequency of strong steering wheel movements etc.) [40, 41]. These generally increase the risk of accidents and are therefore positively correlated with the number of accidents. Moreover, maintaining a proper safety distance, making fewer lane changes, and adhering to speed limits contribute to reduced accident frequencies [40–42]. Furthermore, driver alertness plays a role in reducing accident severity. More alert drivers tend to experience less severe accidents due to their heightened responsiveness and better decision-making [43]. Additionally, adverse weather conditions (e.g. precipitation) increase the likelihood of accidents and potentially amplify their severity [42].

As accidents occur and traffic flow is disrupted, road capacity can diminish due to congestion and lane closures, affecting the overall efficiency of the road network [44]. An illustration of the described interrelations including external connections to variables of other impact categories can be found in Fig. 6.

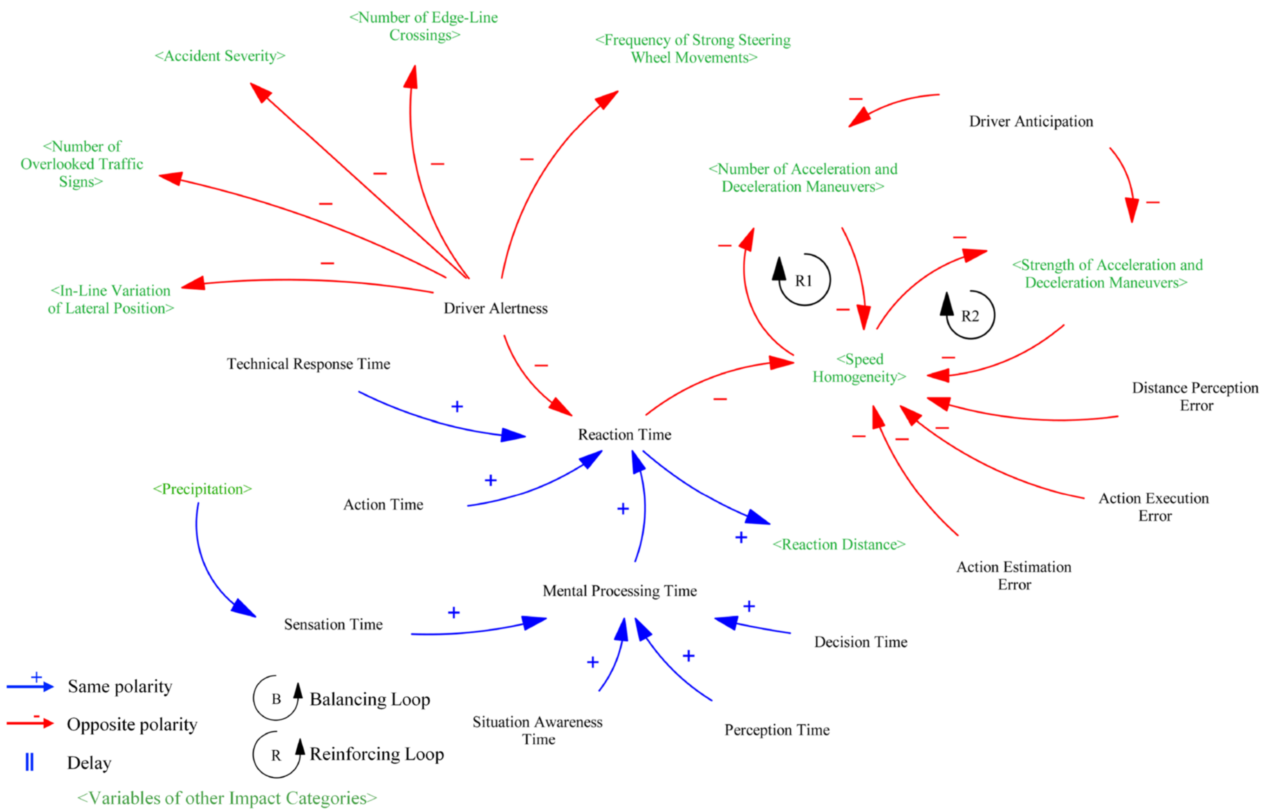

Fig. 5 CLD - Psychological Impact

Ecological impact

Changes in road safety variables have an impact on the area of ecological impact, among others. For example, the deteriorating condition of the road surface can contribute to a higher number of accidents, particularly when road wear leads to decreased traction or hazardous conditions [45]. Furthermore, road wear after some time requires maintenance to preserve road quality, again mitigating the effects of road wear (see B7 in Fig. 7), helping to sustain the road's structural integrity [46]. Moreover, heavier vehicles exert more pressure on the road surface, accelerating its deterioration. Similarly, the road surface is subjected to greater stress due to higher traffic volumes [47, 48].

Road maintenance is also linked to the number of road works aimed at repairing or enhancing road infrastructure [46]. Higher traffic volumes may prompt road authorities to adapt the road structure to accommodate the increased load, such as widening lanes, adding extra lanes or building new roads. This adaptation positively influences road capacity [26–28]. In turn, however, this also leads to an increased number of road works, temporarily decreasing road capacity [44].

Road wear is also related to fuel consumption. Elevated road wear leads to higher rolling resistance, which requires vehicles to expend more energy to generate and maintain their speed. This translates into vehicles consuming more fuel to overcome the added resistance [45, 46]. Fuel consumption is influenced by various factors related to vehicle operation. The number and strength of acceleration and deceleration maneuvers both contribute to increased fuel consumption, since these behaviours require more energy to propel the vehicle forward [25]. Air drag is another determinant of fuel consumption. As speed increases, air drag intensifies, requiring more fuel to overcome this resistance [49–51]. Moreover, the minimum safety distance between vehicles contributes to air drag, since maintaining a shorter distance between vehicles reduces the air drag due to slipstream effects [49, 50].

Fuel consumption, in turn, contributes to emissions [46]. The combustion of fuel in vehicles leads to the release of pollutants and greenhouse gases, impacting environmental quality. The number of road works, the percentage of heavy-duty vehicles as well as the general traffic volume are additional contributors to emissions [46, 52, 53].

An illustration of the described interrelations including external connections to variables of other impact categories can be found in Fig. 7.

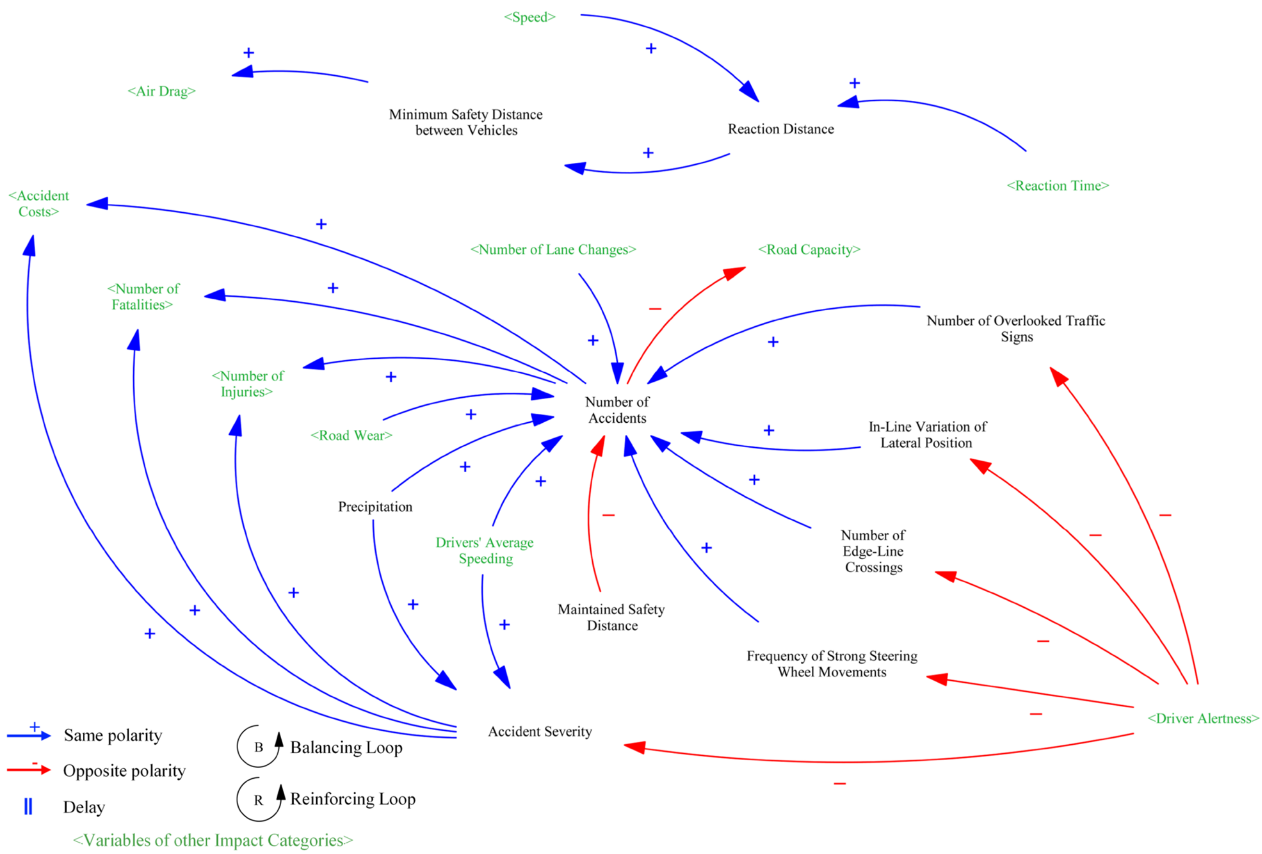

Fig. 6 CLD - Traffic Safety

Socioeconomic impact

The described impacts of the individual categories all lead to socioeconomic impacts in the long run. For example, increased emissions, injuries, and fatalities contribute to a decline in public health indicators, emphasizing the overarching impact of traffic-related incidents on the well-being of society [54, 55]. Both injuries and fatalities are influenced by the number and severity of accidents, as higher accident rates and severities correspond to an increased likelihood of injuries and fatalities occurring within the traffic system [56, 57]. Furthermore, elevated noise levels are associated with negative health implications [54, 58]. Noise level, in turn, is being moderated by several factors. Deteriorated road surfaces and road works as well as heavy vehicles, high traffic volumes, and elevated speeds collectively contribute to higher noise levels in the surrounding environment [45, 59–63].

Moreover, driver satisfaction is a key factor in the social impact of ITS, and is also being influenced by multiple aspects. Delay has a negative effect on driver satisfaction, as prolonged travel times diminish the overall travel experience [64]. Furthermore, improved driver comfort, achieved through factors such as reduced frequency and severity of acceleration and deceleration maneuvers and damage-free road infrastructure, has a positive impact on overall driver satisfaction [45, 65–69].

The impact of ITS services can also be quantified in terms of external costs of transport, either directly or indirectly through follow-up effects, and an economic impact can be derived. A detailed description of these costs and their scope in terms of content can be found in [70]. For example, more severe accidents, increased accident frequencies, and higher numbers of injuries collectively elevate the financial costs associated with accidents (e.g. material costs, medical costs). Altered road structures and increased emissions can negatively impact local habitats (e.g. habitat damage and/or fragmentation, loss of biodiversity). Emissions also contribute to air pollution costs and climate change costs (e.g. medical expenses due to higher risks of respiratory and cardiovascular diseases or heat stress, crop losses, water management issues). Fuel consumption adds to fuel costs as it directly affects the expenses of procuring fuel. And lastly, increased congestion generates costs associated with delays (e.g. value of time, decreased productivity).

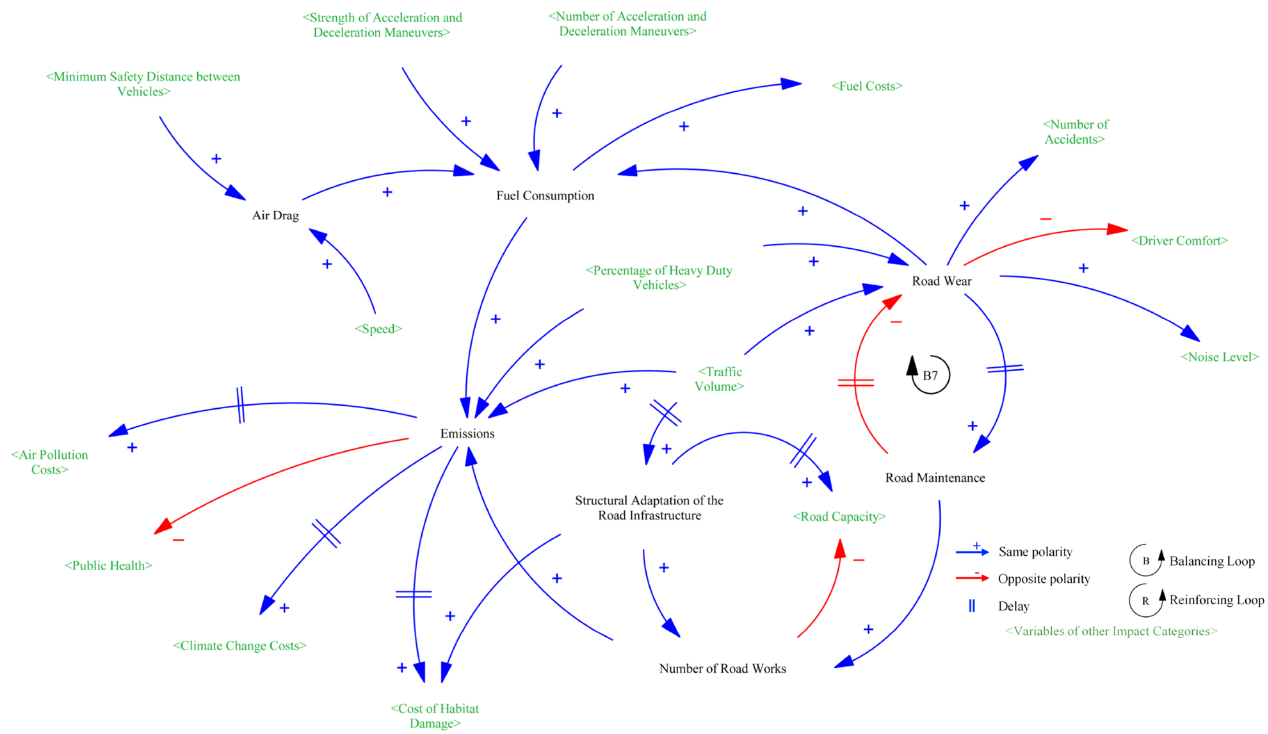

Fig. 7 CLD - Ecological Impact

The combined impact of these externalised costs of road transport places a significant financial burden on society. These costs are often hidden or dispersed, making them challenging to quantify and allocate accurately. However, governments, communities, and institutions must allocate resources to address these costs, leading to increased public spending, reduced economic productivity, and an overall lower quality of life for individuals.

An illustration of the described interrelations including external connections to variables of other impact categories can be found in Fig. 8.

3.2 Baseline causal loop diagram

Combining the CLDs of the individual impact categories created in Sect. 3, the diagram illustrated in Fig. 9 is obtained, which summarises the intricate interactions and interdependencies of different road traffic aspects in one model. A detailed description of the definitions of the impact categories and variables, as well as a description of the connections, polarities and the feedback loops can be found in the appendix.

3.3 CLD-based impact assessment of C-ITS services

The baseline CLD can be used as a basis for qualitative analysis of interactions between the individual impact categories. In this section, the applicability of the CLD is illustrated by two examples, where Use Case I examines a single C-ITS service and Use Case II analyses several C-ITS services simultaneously.

Use Case I: Single C-ITS service

Use Case I focuses on the analysis of the "In-Lane Offset Recommendation and Control" service, a C-ITS application developed within the ESRIUM project [71]. This service works by sending targeted instructions, particularly to heavy-duty vehicles, recommending to adjust their lateral position by a marginal amount within their designated lane, typically a few centimetres. The main purpose of this service is to reduce road wear by promoting a more even distribution of vehicle loads. A detailed explanation can be found in [72].

Incorporating this C-ITS Service into the baseline CLD, the model according to Fig. 10 emerges.

The phenomenon of road wear comprises several intricate relationships within the wider traffic system, as illustrated in the CLD. Examining the impact of road wear on these links reveals a complex network of interdependencies, illustrating how changes in road wear can propagate through the system and have effects on multiple categories.

Firstly, road wear could lead to a subsequent need for road maintenance. This relationship is characterised by a

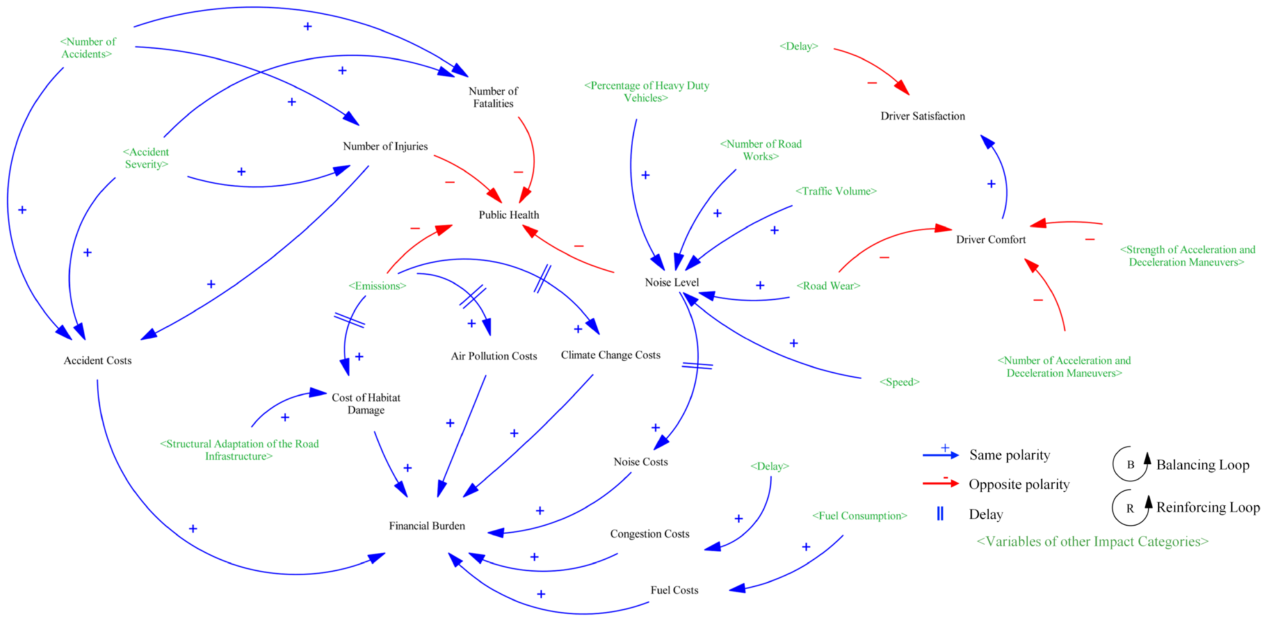

Fig. 8 CLD - Socioeconomic Impact

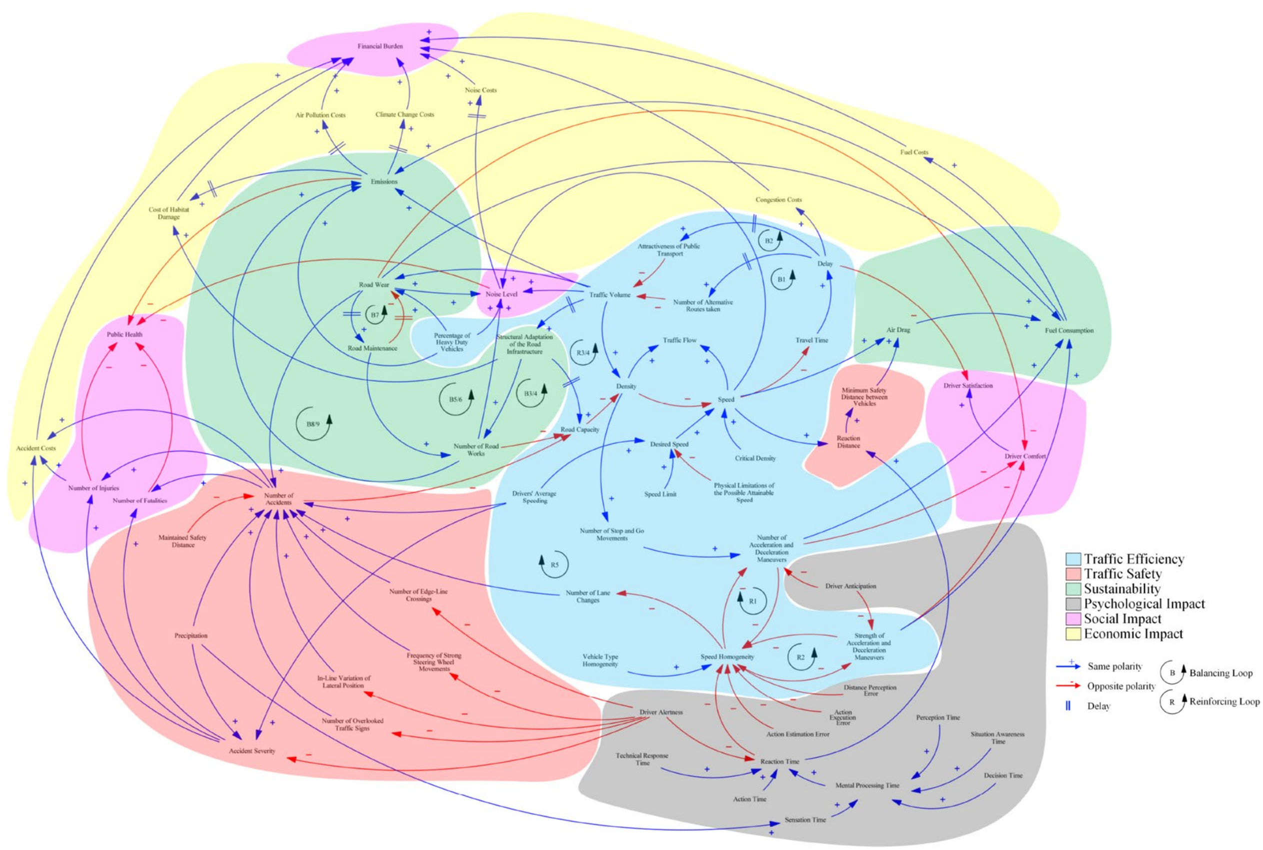

Fig. 9 Baseline CLD for Impact Assessment

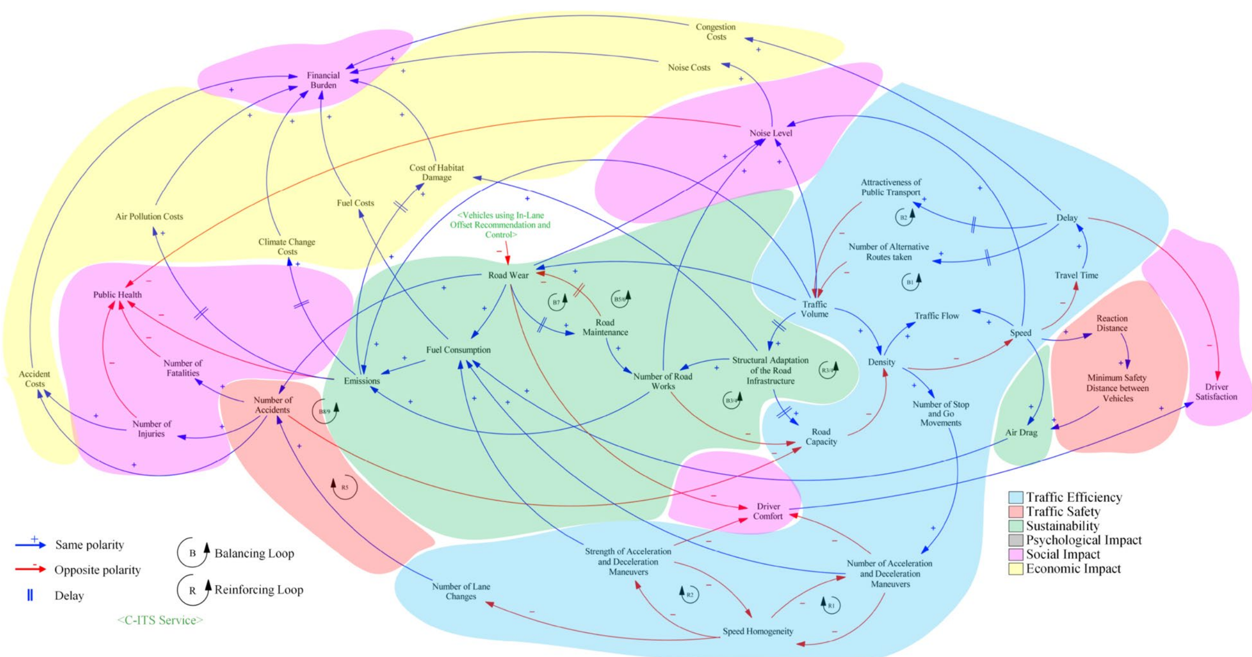

Fig. 10 CLD - Use Case I

time lag, as road wear is not addressed continuously, but only after a certain level of wear has been exceeded. On the other hand, road maintenance acts as a countermeasure to road wear (loop B7; for a detailed description of the feedback loops see Appendix 8).

Beyond that, road wear could lead to a variety of follow-up and rebound effects (e.g. loops B1-B6, R3/4). The temporary restrictions on road capacity due to maintenance work could lead to a shift or fluctuation in traffic volume and might thus reduce the stress on the maintained road, at least temporarily, and delay the need for structural adaptations of the road infrastructure. However, road works may also lead to more stress on alternative routes. Conversely, it can also be deduced that a reduction in road wear through e.g. C-ITS services due to the absence of road maintenance construction sites could lead to more stable and - according to the current trend - increasing traffic volumes, which might result in the need to expand the road infrastructure. The result would be higher road capacity after finishing the structural adaptions of the road infrastructure, and as a consequence further increased traffic volume. But before that, road works might be needed and road capacity is reduced with the consequence of higher delay. A reduction in road wear by the C-ITS service could thus reduce road works for maintenance and resulting delays, but may have a rebound effect, as increasing traffic volumes may require the road infrastructure to be expanded, which again may lead to road works.

Lower traffic densities due to avoidance of construction works as a result of the C-ITS service could influence the occurrence of both stop and go and acceleration and deceleration maneuvers. Consequently, these improve speed homogeneity, and subsequently feed back into reducing the frequency and intensity of these maneuvers (loop R1 and R2). Furthermore, the number of lane changes, a result of higher speed homogeneity, could decrease the frequency of accidents, which results in fewer restrictions on road capacity (loop R5).

The use of the C-ITS Service might not only decrease delays and consequently congestion costs, but also has a positive impact on driver satisfaction. Additionally, driver comfort could be enhanced by the improved road surface and the decreased frequency and intensity of acceleration and deceleration maneuvers.

The complex relationships within the CLD further illustrate the direct impact of reduced road wear on the occurrence and consequences of accidents, as less road damage decreases the risk of accidents. This in turn might impact road capacity (loop B8/9). Additionally, the effects of less road wear cascade further to influence the number of fatalities, injuries and associated accident costs, highlighting the wider safety implications of lower road degradation.

Fuel consumption can be influenced by a decrease in road wear and the potential lower number and intensity of acceleration and deceleration maneuvers. Consequently, emissions drop due to consuming less fuel and the decreaesd number of road works. However, the potential increase in speed has a direct impact on reaction distance, which in turn influences the minimum safety distance that drivers must maintain between vehicles, has a direct impact on air resistance, leads to higher fuel consumption and therefore higher emissions.

On the one hand, the reduced road wear itself, as well as the construction sites that might be saved as a result, lead to less noise. On the other hand, both speed and traffic volume remain at a high level, which are drivers for high noise levels. The improvement or deterioration in the noise level therefore depends on the actual ratio between traffic and construction noise. The change in noise levels, together with the potential decrease in emissions as well injuries and fatalities, have public health implications, affecting both the well-being of individuals and the surrounding environment.

In addition, all variables that change due to decreased road wear contribute in one way or another to various cost factors. Decreased noise levels would lead to lower noise costs, while decreased fuel consumption would lead to lower fuel costs. Decreased emissions can contribute to several factors, such as climate change costs, air pollution costs and habitat damage costs. However, a potential need for structural adjustments to the road infrastructure might counteract the savings in costs related to emissions. All in all, these cost factors add up to a financial burden and show how a reduction in road wear and tear can affect the financial burden on society through a wide variety of impacts, follow-up effects and rebound effects.

In summary, the analysis of interrelations presented in the CLD illustrates the impacts that road degradation creates within a traffic system, and demonstrates the far-reaching impact propagation a C-ITS service developed to reduce road wear could have. The effects of road wear might go beyond surface degradation, affecting everything from road maintenance and traffic behaviour to emissions, noise pollution and financial burdens. Many of the variables presented in the CLD are affected by road wear not just once, but many times through multiple pathways and feedback loops. Understanding these complex effect structures of road wear reduction by using C-ITS is essential for informed decision-making and effective strategies to maintain infrastructure quality, improve safety and optimise the efficiency and sustainability of traffic networks.

Use case II: C-ITS service bundle

The baseline CLD can be used not only for individual services but also for service bundles. Use Case II therefore investigates the impact of a combination of services described in [73]. The C-ITS services Road Hazard Warning, Road Works Warning, Traffic Jam Ahead Warning and Shockwave Dampening are combined as a bundle. A detailed description of the services can be found in [73–76].

The described applications are warning and information services that send messages to vehicles based on certain events in order to increase driver alertness and anticipation [77, 78]. Furthermore, congestion warnings in particular often lead to route changes to avoid the congestion, if this is possible, permitted and perceived beneficial on an individual level.

Incorporating this C-ITS Service bundle into the baseline CLD the model according to Fig. 11 emerges.

The increased use of the C-ITS bundle plays a crucial role in improving driver anticipation. As a result, drivers become better prepared to anticipate the respective changes in the road environment, leading to a reduction in the number and strength of acceleration and deceleration maneuvers. This yields a positive effect on speed homogeneity, indicating a more harmonious traffic flow pattern.

Moreover, by providing drivers with timely information about potential disruptions, these features foster a heightened state of alertness, which is, among others, a critical determinant of reaction time. An alert driver can process information more swiftly, recognise potential hazards earlier, and initiate appropriate responses promptly. As a result, the decrease in reaction time can contribute to higher speed homogeneity. Consequently, the reduction in traffic speed variations through the use of the C-ITS services might lead to a decrease in the number of lane changes and thus a lower likelihood of accidents. Furthermore, increased alertness facilitated by these warning applications reduces the likelihood of driving errors, which might also lead to a decrease in the number of accidents. Additionally, driver alertness can shape accident severity, which, alsongside the number of accidents, might influence the number of fatalities, injuries, and the overall accident costs.

Similar to Use Case I, the impacts of the C-ITS Services can extend to the broader context of traffic efficiency. The potential reduction in the number of accidents can lead to an increase in road capacity and thus to a reduction in density. This congestion avoidance in turn might lead to fewer stop-and-go and to fewer acceleration and deceleration maneuvers, which in turn reduces the probability of accidents via follow-up effects (loop R5).

However, lower traffic density can also lead to higher speeds, shorter travel times and thus less delay, which would result in lower congestion costs and, at the same time, higher driver satisfaction. As described in Use Case I, driving comfort is essential for driver satisfaction, which, in addition to road wear, is also influenced by the frequency and intensity of braking and acceleration

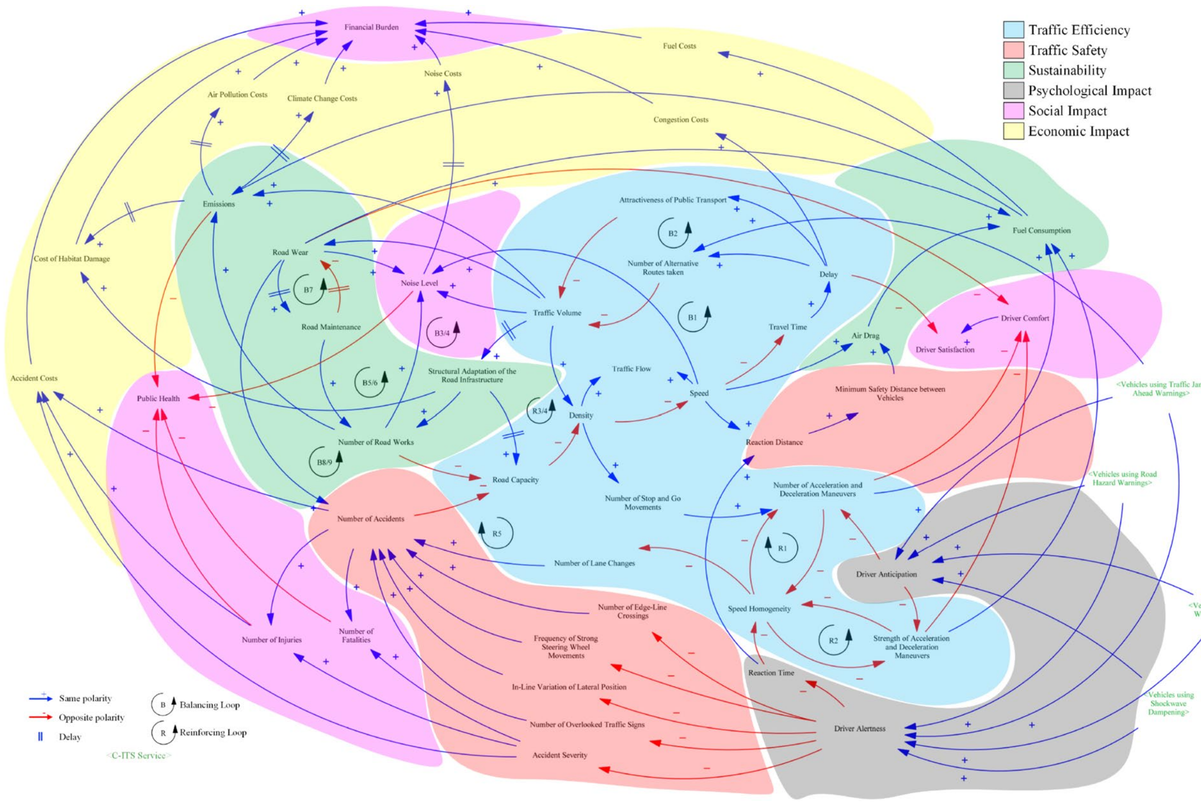

Fig. 11 CLD - Use Case II

maneuvers and might therefore be increased by the use of C-ITS services via consequential effects.

The delay influences the behaviour of road users in terms of the choice of transport mode and route. At the same time, traffic jam warnings in particular often lead to route changes in order to avoid delays. Depending on the general trend, this might either reduce or slow down growth in traffic volume, which would again lead to a set of follow-up effects. For example, a change in traffic volume leads to a change in density, which in turn triggers follow-up effects in loops B1 and B2.

However, the potential reduction or slowed down increase in traffic volume does have an impact on the progression of road wear, might result in a delay of road maintenance, the number of road works, and could contribute to the preservation of road capacity (with follow-up effects via the B3/4 loop). In addition, the lower road wear could also reduce the probability of accidents, which in turn would have positive consequential effects on the traffic flow via loop B8/9.

The potentially reduced road wear and the lower frequency and intensity of acceleration and deceleration as a result of using the C-ITS bundle can have a positive effect on fuel consumption, which, together with a reduction of road works and traffic volume, can lead to lower emissions. Furthermore, the shortened reaction time due to the increased alertness provided by C-ITS services allows for a smaller safety distance between vehicles, which reduces air drag and, as a result, leads to a reduction in fuel consumption and emissions.

Similarly, noise levels can be influenced through the use of C-ITS services via follow-up effects. Additionally, changes in emissions and fatalities and injuries as a result of reduced probability of (severe) accidents contribute to public health.

Finally, the effects of the considered C-ITS service bundle are reflected in the external costs of transport. Thus, potential emission reductions would lead to a decrease in the costs of habitat damage, costs of climate change and air pollution costs. Overall, as outlined, the use of C-ITS services also reduces the financial burden through various follow-up effects.

In summary, the integration of the C-ITS service bundle described has a wide range of effects on the traffic system. These range from improving driver anticipation and alertness, reducing acceleration and braking maneuvers, improving traffic flow, influencing ecological aspects, to public health impacts and various financial factors. These complex interactions emphasise the potential of these advanced technologies for designing safer, more efficient and sustainable transport systems.

4 Conclusion

In this paper, a CLD is presented that illustrates the interrelations, follow-up effects and rebound effects of C-ITS service impacts. This approach allows for the incorporation of single or multiple C-ITS services as separate modules, each with their own distinct connections to the model's variables. Consequently, the impact propagation of these services across the overall system can be systematically analysed. These results contribute to answering RQ1.

Furthermore, illustrative examples of the use of the CLDs and the analysis of C-ITS service (bundles) were presented in the context of two use cases, demonstrating the far-reaching impact propagation of such applications in order to answer RQ2. Both examples, underscore the intricate web of relationships within the traffic system, as C-ITS services or service bundles influence a variety of factors in multiple ways, ranging from driver behaviour and traffic efficiency to environmental and socioeconomic aspects. The results of the use case illustrations highlight the need to consider dependencies and interactions between individual C-ITS impact categories.

However, there are limitations to the approach described. Thus, the system model only represents a partial view of the overall traffic system. There may be variables not taken into account that that could potentially be included in subsequent investigations, thereby introducing additional feedback loops and rebound effects. Furthermore, while the general direction of influence within the CLD can be reasonably inferred, precise quantification of the results remains elusive. The use of CLDs alone therefore does not allow an exact determination of the magnitude of the impact. Nevertheless, the methodology applied is particularly useful for identifying and estimating cascading and rebound effects of C-ITS solutions. Consequently, this work aids researchers in developing comprehensive impact assessment studies by considering and integrating the potential impact propagation and rebound effects outlined in the CLD in advance. In order to provide a quantitative assessment that includes both the magnitude of the impact and the rebound effects, future research can use the developed CLD as a basis for the construction of Stock-Flow Models.

In summary, the findings of this research in terms of the presented CLDs contribute to a comprehensive impact assessment of C-ITS services, providing policy-makers and researchers with valuable insights to advance the development and implementation of C-ITS. The results of this work show that the effects of C-ITS are on the one hand far-reaching and on the other hand not necessarily unidirectional, but can lead to rebound effects via consequential effects. By acknowledging the system of interdependencies and reciprocities between impact categories, this study offers a nuanced perspective on the potential benefits and challenges associated with C-ITS. The results of this work therefore represent another important step towards a holistic impact assessment and form the basis for designing future impact assessment studies targeted towards the revealed interrelations.

Appendix A List of abbreviations

CCAM	Cooperative Connected and Automated Mobility
C-ITS	Cooperative Intelligent Transport System
CLD	Causal Loop Diagram
ICT	Information and Communication Technology
ITS	Intelligent Transport System
V2I	Vehicle-to-Infrastructure
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything

Appendix B Definition of variables and impact categories

Accident Severity Accident severity refers to the extent of harm, damage, or negative consequences resulting from an accident or incident (injuries, fatalities, material damage) (modified definition based on [56])

Accident costs External costs incurred due to traffic accidents. These include human costs (e.g. estimation of pain and suffering caused by accidents in monetary value), medical costs (e.g. costs of the victim's medical treatment provided by hospitals, rehabilitation centres and costs of appliances and medicines), administrative costs (e.g. costs of the deployed emergency service, legal costs and insurance costs), production losses (e.g. net production losses due to reduced working time and human capital replacement costs), material damages (e.g. monetary value of damages to vehicles, infrastructure, freight and personal property), and other costs, such as costs of congestion, vehicle unavailability, funeral costs etc. [70]

Action time The time it takes to carry out an action (e.g. moving a foot to the brake pedal) [25]

Action execution error Action execution errors refer to the errors in maneuvering mechanical components of a vehicle [29]

Action estimation error Action estimation means the process of assessing the effects of the actions on the own vehicle or of other vehicles. An estimation error describes a misjudgement of these actions or the required strength of one's own action [29]

Air pollution costs External costs incurred due to air pollution. These include health effects (e.g. medical treatment cost and production loss due to higher risks of respiratory and cardiovascular diseases), crop loss (e.g. damage of agricultural crops due to acidic air pollutants), material and building damage (e.g. pollution of building surfaces as well as damage of building facades), and biodiversity loss (e.g. acidification of soil, precipitation and water as well as eutrophication of ecosystems) [70]

Air drag Air drag is a force exerted by air (or in case of drag any fluid) on an object moving through it. This force opposes the motion of the object and is caused by the interactions between the object and the molecules it encounters [50]

Attractiveness of public transport Tendency of road users to favour public transport over private transport for a certain trip [own definition]

Climate change costs External costs associated with all of the effects of global warming. These include (among others) sea level rise, biodiversity loss, water management issues, more frequent weather extremes and crop failures. For road, rail, inland waterway and maritime transport, the global warming impacts of transport are mainly caused by CO_2, N_2O and CH_4 [70]

Congestion costs External costs associated with delays due to congestion. Congestion costs are defined as the value of the travel time lost relative to a free-flow situation [70]

Cost of habitat damage External costs associated with all of the effects on nature and landscapes. These include habitat loss (e.g. due to required land for transport infrastructure), habitat fragmentation (e.g. due to required land for transport infrastructure and transport demand), and habitat degradation (e.g. due to emission of air pollutants) [70]

Critical density According to the fundamental diagram of traffic flow, the critical traffic density refers to the point at which a roadway or transportation network reaches the maximum traffic flow. Beyond this density, additional vehicles entering the system lead to reduced traffic flow [24]

Decision time The time it takes to decide on how to react to a situation [25]

Delay The additional travel time required compared to the travel time calculated on the basis of freeflow traffic [own definition]

Density The traffic density is defined as the number of vehicles on a road segment at a given time. It is measured in the number of vehicles per unit of distance [22, 25]

Desired speed The desired speed describes the speed that can be achieved under free-flow conditions (low-density traffic). It depends, among other things, on the actual desired speed of the drivers, physical limitations of the possible attainable speed, speed limits and a drivers' average speeding [25]

Driver satisfaction refers to the contentment, fulfillment, and positive feelings experienced by individuals who are operating a vehicle. It encompasses factors related to the driving experience that contribute to the overall sense of well-being while on the road [own definition]

Driver comfort refers to the level of physical well-being experienced by a person while operating a vehicle [own definition]

Driver anticipation refers to the proactive and forward-thinking approach that a driver takes while operating a vehicle. It involves the ability to predict and foresee potential hazards, changes in traffic conditions, and the behavior of other road users [29]

Driver alertness Driver alertness refers to a state of heightened attentiveness, and cognitive awareness exhibited by a person who is operating a vehicle [own definition]

Drivers' average speeding The average tendency of drivers to exceed the speed limits [25]

Ecological impact The impact category ecological impact summarizes all ecological effects of C-ITS such as fuel consumption, energy consumption, and air pollution (e.g. emissions, particulate matter), but also factors regarding the transport infrastructure (e.g. road wear, number of road works) [own definition]

Economic impact The impact category economic impact includes the effects of the respective services on costs for individuals or society in terms of externalized costs of transport (e.g. costs of climate change, accident costs, air pollution costs) [own definition]

Emissions Emissions refer to the pollutants and harmful substances released into the environment as a result of vehicular traffic (e.g. CO_2, CO, NO_x, PM_x, HC, VOC) [46, 70]

Financial burden Financial burden refers to the costs imposed on society (e.g. individuals, households, organisations, etc.) [own definition]

Frequency of strong steering wheel movements The number of significant or abrupt adjustments of the steering wheel while operating a vehicle [own definition]

Fuel costs Fuel costs refer to the expences for purchasing fuel to power vehicles [own definition]

Fuel consumption Fuel consumption refers to the amount of fuel that a vehicle or engine uses over a specific distance or period of time [own definition]

In-line variation of lateral position In-line variation of lateral position refers to the degree to which a vehicle deviates from its intended straight-line path along a road lane [own definition]

Maintained safety distance Safety distance refers to the bumper-to-bumper distance maintained between vehicles while in motion, in order to react to unexpected situations and avoid accidents [25]

Mental processing time The mental processing time refers to the timespan between sensing a situation and the decision on an action [25]

Minimum safety distance between vehicles The minimum safety distance between vehicles describes the minimum distance between vehicles where necessary (abrupt) full stops would not result in an accident [25]

Noise level Noise level refers to the measurement of sound intensity or volume in relation to road traffic (e.g. by vehicles, inftrastructure, maintenance activities) [own definition]

Noise costs External costs associated with traffic noise, which subsume e.g. medical costs due to higher risks of ischaemic heart diseases, strokes, dementia, hypertension and annoyance as well as costs for noise abatement efforts (i.e. costs for building noise dampening walls) [70]

Number of stop and go movements The number of stop and go movements refers to the count of instances where a vehicle comes to a complete stop and then accelerates to resume motion [own definition]

Number of road works The number of road works refers to the count of construction, or maintenance activities taking place on the transportation infrastructure [own definition]

Number of overlooked traffic signs The number of overlooked traffic signs refers to the count of instances where drivers fail to notice or acknowledge the presence of road traffic signs while driving [own definition]

Number of lane changes The number of lane changes refers to the count of times a vehicle changes its position from one lane to another while traveling on a road [own definition]

Number of injuries The number of injuries refers to the count of individuals who have sustained physical harm, injury, or bodily damage as a result of an incident. In the context of road accidents, this term indicates the total count of individuals who have been harmed or injured due to collisions [own definition]

Number of fatalities The number of fatalities refers to the count of individuals who have died as a result of a particular incident. In the context of road accidents, it indicates the total count of individuals who lost their lives due to collisions [own definition]

Number of edge-line crossings The number of edge-line crossings refers to the count of instances where a vehicle's tires or wheels cross the edge lines of a road or lane [own definition]

Number of alternative routes taken The number of alternative routes refers to the count of journeys deviating from the fastest route based on free flow travel time. It encompasses shifts in route and mode choice, influenced by factors like congestion avoidance and the consolidation of activities due to longer travel times [own definition]

Number of accidents The number of accidents refers to the count of incidents in which vehicles and people are involved in collisions or other unfortunate events that cause harm or disruption [own definition]

Number of acceleration and deceleration maneuvers The number of acceleration and deceleration maneuvers refers to the count of instances where a vehicle accelerates (increases its speed) or decelerates (reduces its speed) [own definition]

Percentage of heavy duty vehicles The percentage of heavy-duty vehicles refers to the proportion of all vehicles on a road that fall into the category of heavy-duty vehicles [own definition]

Perception time Perception time refers to the duration it takes to organize sensed information [25]

Perception error Perception errors refer to measurement errors for distance or speed of the vehicle in front [29]

Physical limitations of the possible attainable speed Physical limitations of the possible attainable speed refers to the inherent constraints and boundaries that prevent an object or vehicle from achieving higher speeds based on the laws of physics and the design of the object itself. (e.g. for trucks on uphill slopes, sharp curves) [25]

Precipitation Precipitation refers to any form of water, liquid or solid, that falls from the atmosphere and reaches the Earth's surface [own definition]

Psychological impact The impact category psychological impact comprises all indicators measuring the effect that C-ITS can have on the mental and emotional states of road users, such as cognitive, emotional, and behavioural responses (e.g. alertness, reaction times, distraction) [own definition]

Public health Public health refers to the health and well-being of entire populations, communities, and societies [own definition]

Reaction time Reaction time is the time that elapses from the recognition of a situation to the start of the necessary corrective action [25]

Reaction distance Reaction distance refers to the distance a vehicle travels from the moment a driver perceives a hazard or an unexpected situation to the moment they begin to take evasive actions [25]

Road wear Road wear refers to the gradual deterioration or damage that occurs to road surfaces and infrastructure over time due to the effects of traffic, weather, and other factors [own definition]

Road maintenance Road maintenance refers to a set of activities aimed at preserving, repairing, and ensuring the safe and efficient condition of roads [own definition]

Road capacity Road capacity refers to the maximum number of vehicles that a road or a specific lane can accommodate without causing congestion or significant decreases in travel speed [25]

Sensation time The time it takes to sense (see, hear etc.) a specific situation [25]

Situation awareness time The time it takes to cognitively process and understand a situation [25]

Social impact The impact category social impact encompasses indicators referring to the effects of C-ITS on individuals and communities (e.g. public health, comfort, financial burden) [own definition]

Socioeconomic impact The impact category socioeconomic impact subsumes both categories social impact and economic impact [own definition]

Speed Speed refers to the rate at which a vehicle moves or travels over a certain distance within a specific time interval [own definition]

Speed limits Speed limits refer to the legally established maximum or minimum speeds at which vehicles are allowed to travel on specific road segments [own definition]

Speed homogeneity Speed homogeneity refers to the uniformity of vehicle speeds among traffic participants. In a speed-homogeneous traffic, the vehicles are traveling at similar speeds without significant variations [own definition]

Strength of acceleration and deceleration maneuvers The strength of acceleration and deceleration maneuvers refers to the intensity or force with which a vehicle increases or decreases its speed [own definition]

Structural adaption of the road infrastructure Structural adaptation of road infrastructure refers to modifications made to the layout of the traffic infrastructure to enhance road capacity [own definition]

Technical response time Technical response time refers to the duration it takes for a vehicle component to react and provide a desired response after receiving a stimulus [25]

Traffic volume Traffic volume refers to the total number of vehicles travelling on a given road network [own definition]

Traffic safety The impact category traffic safety encompasses all indicators used to describe the accident situation (e.g. type of accidents, number of accidents/injuries) and indicators used to estimate the effects of C-ITS on accident probability [own definition]

Traffic flow The flow of traffic is defined as the number of vehicles that pass through a point in a unit of time [22]

Traffic efficiency The impact category traffic efficiency subsumes all indicators describing the way in which different (groups of) entities move within a transportation system (e.g. speed, acceleration, travel time, traffic flow, number of lane changes, transport mode, route choice) [own definition]

Travel time The travel time refers to the amount of time it takes to travel between two specific points or locations [own definition]

Vehicle type homogeneity Vehicle type homogeneity refers to the similarity or uniformity of the types of vehicles present within traffic [own definition]

Appendix C CLD-variables

See Appendix Tables 1, 2

Table 1 Cause-Effect Relations

Cause-effect relation	Evidence discussed
Accident Costs $\xrightarrow{+}$ Financial Burden	The more accident costs accumulate, the greater the economic strain placed on society.
Accident Severity $\xrightarrow{+}$ Accident Costs	Accidents with higher severity levels tend to result in higher financial expenses due to the more extensive injuries and property damage involved (e.g. higher material damages) [70].
Accident Severity $\xrightarrow{+}$ Number of Fatalities	Accidents with higher severity levels are more likely to result in fatalities due to the greater extent of injuries and potential life-threatening circumstances [56, 57].
Accident Severity $\xrightarrow{+}$ Number of Injuries	Accidents with higher severity levels are more likely to result in a greater number of injuries [56, 57].
Action Estimation Error $\xrightarrow{-}$ Speed Homogeneity	When drivers make errors in estimating the appropriate level of acceleration or deceleration, speed variations in traffic tend to increase [29].
Action Execution Error $\xrightarrow{-}$ Speed Homogeneity	When drivers make errors in executing the appropriate level of acceleration or deceleration, speed variations in traffic tend to increase [29].
Action Time $\xrightarrow{+}$ Reaction Time	When drivers take longer to carry out planned actions, they also take longer to react to unexpected events or hazards that require immediate responses [25, 37].
Air Drag $\xrightarrow{+}$ Fuel Consumption	When a vehicle experiences higher air drag due to increased speed or less aerodynamic design, it requires more energy (fuel) to overcome the resistance and maintain its speed [25, 49–51].
Air Pollution Costs $\xrightarrow{+}$ Financial Burden	The more air pollution costs accumulate, the greater the economic strain placed on society.
Attractiveness of Public Transport $\xrightarrow{-}$ Traffic Volume	When public transportation becomes more appealing and convenient, more individuals may choose to use public transport instead of private vehicles, resulting in fewer vehicles on the road [26–28].
Climate Change Costs $\xrightarrow{+}$ Financial Burden	The more climate change costs accumulate, the greater the economic strain placed on society.
Congestion Costs $\xrightarrow{+}$ Financial Burden	The more congestion costs accumulate, the greater the economic strain placed on society.
Costs of Habitat Damage $\xrightarrow{+}$ Financial Burden	The more costs of habitat damage accumulate, the greater the economic strain placed on society.
Critical Density $\xrightarrow{+}$ Speed	The higher the critical density, the higher speeds can be driven for a given traffic density [24].
Decision Time $\xrightarrow{+}$ Mental Processing Time	When drivers take longer to make decisions, it also takes them longer to mentally process the information, evaluate choices, and formulate an appropriate response [25, 37].
Delay $\xrightarrow{-}$ Driver Satisfaction	When drivers experience longer delays and slower travel speeds, their satisfaction with the travel experience tends to decrease [64].
Delay $\xrightarrow{+}$ Congestion Costs	As delays accumulate and traffic congestion worsens, the associated economic costs also increase due to factors such and lost productivity and value of time [70].
Delay $\xrightarrow{+(\text{with time lag})}$ Attractiveness of Public Transport	When people experience longer delay times using private vehicles due to congestion or other factors, they may be more inclined to consider and adopt public transportation options as an alternative [26–28].
Delay $\xrightarrow{+(\text{with time lag})}$ Number of Alternative Routes taken	As commuters experience longer delays due to congestion or other factors, they may gradually start exploring and adopting alternative routes that are perceived to be faster or less congested [26–28].
Density $\xrightarrow{-}$ Speed	According to the fundamental diagram, an increase in traffic density results in an increase of speed (see Equation 2) [22].
Density $\xrightarrow{+}$ Number of Stop and Go Movements	The number of stop and go movements increases in unstable (congested) traffic conditions. Therefore, an increase in density leads to an increase in the number of stop and go movements [29].
Density $\xrightarrow{+}$ Traffic Flow	According to the fundamental diagram, an increase in traffic density results in a decrease of traffic flow (see Equation 3) [22].
Desired Speed $\xrightarrow{+}$ Speed	When drivers desire to travel at a certain speed, they may accelerate or decelerate their vehicles to achieve that speed [25].
Distance Perception Error $\xrightarrow{-}$ Speed Homogeneity	When drivers make errors in estimating the disctance between vehicles, they might need to take corrective actions, thus speed variations in traffic tend to increase [29].
Driver Alertness $\xrightarrow{-}$ Accident Severity	When drivers are more alert and attentive, they are better equipped to perceive and respond to potential hazards, thereby reducing the likelihood of accidents and their associated severity [43].
Driver Alertness $\xrightarrow{-}$ Frequency of Strong Steering Wheel Movements	When drivers are alert and attentive, they make fewer forceful and abrupt steering corrections, as they are more focused [40, 41].
Driver Alertness $\xrightarrow{-}$ In-Line Variation of Lateral Position	When drivers are alert and attentive, their in-line driving trajectoy varies less as they are more focused [40, 41].
Driver Alertness $\xrightarrow{-}$ Number of Edge-Line Crossings	When drivers are alert and attentive, they make fewer edge-line crossings, as they are more focused [40, 41].

Table 1 (continued)

Cause-effect relation	Evidence discussed
Driver Alertness $\xrightarrow{-}$ Number of Overlooked Traffic Signs	When drivers are alert and attentive, they overlook fewer traffic signs, as they are more focused [40, 41].
Driver Alertness $\xrightarrow{-}$ Reaction Time	When drivers are alert and attentive, their cognitive processes are faster and more efficient, resulting in quicker reactions to any situation [40].
Driver Anticipation $\xrightarrow{-}$ Number of Acceleration and Deceleration Maneuvers	When drivers anticipate road conditions and the actions of other road users effectively, they are more likely to adjust their driving behaviors proactively, avoiding the need for frequent speed changes [29].
Driver Anticipation $\xrightarrow{-}$ Strength of Acceleration and Deceleration Maneuvers	When drivers anticipate road conditions and the actions of other road users effectively, they are more likely to adjust their driving behaviors proactively, resulting in smoother and more controlled changes in acceleration and deceleration [29].
Driver Comfort $\xrightarrow{+}$ Driver Satisfaction	When drivers experience a higher level of comfort while driving, they are more likely to be satisfied with their travel experience [69].
Drivers' Average Speeding $\xrightarrow{+}$ Accident Severity	When drivers consistently exceed speed limits or engage in unsafe speeding behavior, the likelihood of accidents occurring at higher speeds increases. Higher-speed accidents are often associated with more severe injuries and damage [43].
Drivers' Average Speeding $\xrightarrow{+}$ Desired Speed	When drivers engage in speeding behavior, it may influence their perception of what constitutes an acceptable or appropriate driving speed, leading them to desire higher speeds [25].
Drivers' Average Speeding $\xrightarrow{+}$ Number of Accidents	When drivers consistently exceed speed limits or engage in unsafe speeding behavior, the likelihood of accidents occurring increases [43].
Emissions $\xrightarrow{-}$ Public Health	Higher levels of emissions and air pollutants can negatively affect air quality and environmental conditions, which, in turn, can have adverse effects on public health, including respiratory problems, cardiovascular issues, and other health-related concerns [54, 55].
Emissions $\xrightarrow{+(\textit{with time lag})}$ Air Pollution Costs	Higher levels of emissions contribute to increased air pollution, which, over time, results in various costs regarding health, crop loss, material and building damage and biodiversity loss [70].
Emissions $\xrightarrow{+(\textit{with time lag})}$ Climate Change Costs	Higher levels of emissions contribute to increased or accelerated climate change, which, over time, results in various costs as a result of sea level rise, biodiversity loss, water management issues and more frequent weather extremes [70].
Emissions $\xrightarrow{+(\textit{with time lag})}$ Cost of Habitat Damage	Higher levels of emissions contribute to increased habitat damage, which, over time, results in various costs regarding habitat loss, fragmentation and degradation [70].
Frequency of Strong Steering Wheel Movements $\xrightarrow{+}$ Number of Accidents	When drivers frequently need to make sudden and abrupt steering maneuvers, it suggests that they are encountering hazardous situations that can result in collisions or accidents. Similarly, these abrupt driving maneuvers can also lead to accidents [40, 41].
Fuel Consumption $\xrightarrow{+}$ Emissions	When vehicles burn more fuel, they produce a greater amount of pollutants and harmful substances as byproducts of combustion [46].
Fuel Consumption $\xrightarrow{+}$ Fuel Costs	When vehicles or machines burn more fuel, the associated expenses for purchasing that fuel also increase.
Fuel Costs $\xrightarrow{+}$ Financial Burden	The more fuel costs accumulate, the greater the economic strain placed on society.
In-Line Variation of Lateral Position $\xrightarrow{+}$ Number of Accidents	When there is greater lateral movement within a lane, it suggests unstable or unpredictable driving behavior, increasing the likelihood of collisions and accidents [40, 41].
Maintained Safety Distance $\xrightarrow{-}$ Number of Accidents	When drivers maintain a greater distance from the vehicle ahead, they have more reaction time and space to respond to sudden changes in traffic conditions, reducing the likelihood of rear-end collisions and other accidents [42].
Mental Processing Time $\xrightarrow{+}$ Reaction Time	When drivers take longer to mentally process current situations, they also take longer to react to unexpected events or hazards that require immediate responses [25, 37].
Minimum Safety Distance between Vehicles $\xrightarrow{+}$ Air Drag	When drivers maintain a larger gap between their vehicle and the vehicle ahead, it can result in reduced aerodynamic efficiency due to increased air resistance [49–51].
Noise Costs $\xrightarrow{+}$ Financial Burden	The more noise costs accumulate, the greater the economic strain placed on society.
Noise Level $\xrightarrow{-}$ Public Health	Higher noise levels can have negative effects on public health, including increased stress, sleep disturbances, and potential negative impacts on cardiovascular and mental health [54, 58].
Noise Level $\xrightarrow{+(\textit{with time lag})}$ Noise Costs	Higher noise levels contribute to increased noise costs, such as medical costs due to higher risks of ischaemic heart diseases, strokes, dementia, hypertension and annoyance as well as costs for noise abatement efforts (i.e. costs for building noise dampening walls) [70].
Number of Acceleration and Deceleration Maneuvers $\xrightarrow{-}$ Speed Homogeneity	When drivers frequently engage in abrupt speed changes, it can disrupt the overall flow of traffic and lead to speed differences among vehicles [31].
Number of Acceleration and Deceleration Maneuvers $\xrightarrow{-}$ Driver Comfort	When drivers frequently experience abrupt speed changes due to rapid accelerations and decelerations, it can lead to a less comfortable driving experience, potentially causing stress, fatigue, and discomfort [65–67].

Table 1 (continued)

Cause-effect relation	Evidence discussed
Number of Acceleration and Deceleration Maneuvers $\xrightarrow{+}$ Fuel Consumption	When drivers frequently engage in abrupt speed changes, it results in more energy being expended to accelerate and decelerate the vehicle, ultimately leading to higher fuel consumption [25].
Number of Accidents $\xrightarrow{-}$ Road Capacity	When accidents occur frequently on a road, it can result in lane closures, road closures, and the need for traffic management measures. This, in turn, reduces the effective capacity of the road [44].
Number of Accidents $\xrightarrow{+}$ Accident Costs	When the frequency of accidents rises, it results in higher expenses related to addressing the consequences of those accidents [70].
Number of Accidents $\xrightarrow{+}$ Number of Fatalities	When accidents occur more frequently, it increases the likelihood of fatalities, resulting in a higher count of lives lost [42, 56, 57].
Number of Accidents $\xrightarrow{+}$ Number of Injuries	When accidents occur more frequently, it increases the likelihood of people sustaining injuries, resulting in a higher count of individuals harmed [42, 56, 57].
Number of Alternative Routes taken $\xrightarrow{-}$ Traffic Volume	When more drivers choose alternative routes, it reduces the number of vehicles on the main route, thereby decreasing the overall traffic volume on the main route [26–28].
Number of Edge-Line Crossings $\xrightarrow{+}$ Number of Accidents	When vehicles cross the edge lines of the road frequently, it increases the risk of collisions, sideswipes, and other accidents [40, 41].
Number of Fatalities $\xrightarrow{-}$ Public Health	When fatalities occur due to accidents, it has negative impacts on the health and well-being of individuals and the community [54].
Number of Injuries $\xrightarrow{-}$ Public Health	When injuries occur due to accidents, it has negative impacts on the health and well-being of individuals and the community [40, 41].
Number of Injuries $\xrightarrow{+}$ Accident Costs	An increased number of injuries results in higher financial expenses due to higher medical costs [70].
Number of Lane Changes $\xrightarrow{+}$ Number of Accidents	When drivers change lanes frequently, it increases the complexity of traffic interactions and the potential for collisions and accidents [42].
Number of Overlooked Traffic Signs $\xrightarrow{+}$ Number of Accidents	When drivers overlook traffic regulations, it increases the likelihood of unsafe behaviors, decreases predictability, and heightens the risk of collisions and accidents [40, 41].
Number of Road Works $\xrightarrow{-}$ Road Capacity	When road works are ongoing, it often involves lane closures, detours, or reduced traffic flow due to construction activities. These disruptions can lead to decreased effective road capacity during the road works [30].
Number of Road Works $\xrightarrow{+}$ Emissions	When road works are ongoing, traffic may be diverted or slowed down, leading to idling vehicles and stop-and-go traffic. These conditions can result in higher emissions of pollutants and greenhouse gases. Furthermore, construction sites per se (material deliveries, operation of construction site equipment, etc.) contribute to higher emissions [46].
Number of Road Works $\xrightarrow{+}$ Noise Level	When road works are ongoing, construction equipment, machinery, and other activities generate noise, contributing to higher overall noise levels in the surrounding area [63].
Number of Stop and Go Movements $\xrightarrow{+}$ Number Acceleration and Deceleration Maneuvers	When traffic conditions result in frequent stop and go movements, drivers have to frequently accelerate and decelerate to adjust to changing speeds and conditions [30].
Percentage of Heavy Duty Vehicles $\xrightarrow{+}$ Emissions	When the proportion of heavy-duty vehicles on the road is higher, it can contribute to higher emissions of pollutants and greenhouse gases due to the typically larger engines and higher fuel consumption of these vehicles [52, 53].
Percentage of Heavy Duty Vehicles $\xrightarrow{+}$ Noise level	When the proportion of heavy-duty vehicles on the road is higher, it can contribute to higher overall noise levels due to the noise generated by their engines, braking systems, and other operations [59].
Percentage of Heavy Duty Vehicles $\xrightarrow{+}$ Road Wear	When the proportion of heavy-duty vehicles on the road is higher, it can result in greater wear and tear on the road infrastructure due to their larger size and weight compared to passenger vehicles [47, 48].
Perception Time $\xrightarrow{+}$ Mental Processing Time	When drivers take longer to perceive a situation, it also takes them longer to mentally process the information, evaluate choices, and formulate an appropriate response [25, 37].
Physical Limitations of the Possible Attainable Speed $\xrightarrow{-}$ Desired Speed	When the physical limitations of a vehicle or road conditions restrict how fast a vehicle can (safely) travel, drivers may need to adjust their desired speed to match the feasible and (safe) speed [25].
Precipitation $\xrightarrow{+}$ Accident Severity	When precipitation occurs, road surfaces can become slippery and visibility can be reduced, increasing the likelihood of accidents. These adverse conditions can lead to accidents with more severe outcomes in terms of damage and injuries [43].
Precipitation $\xrightarrow{+}$ Number of Accidents	When precipitation occurs, road surfaces can become slippery, visibility can be reduced, and overall driving conditions can become more challenging. These adverse conditions can lead to an increase in the likelihood of accidents [42, 43].

Table 1 (continued)

Cause-effect relation	Evidence discussed
Precipitation $\xrightarrow{+}$ Sensation Time	Precipitation can influence the sensation time of drivers by reducing visibility, leading to a heightened sensory load and potentially slower response to stimuli [38, 39].
Reaction Time $\xrightarrow{-}$ Speed Homogeneity	When the driver's reaction time is longer, driving maneuvers, such as speed adjustment, will be delayed, resulting in a higher decrease of speed homogeneity [25, 35, 36].
Reaction Distance $\xrightarrow{+}$ Minimum Safety Distance between Vehicles	When a driver's reaction distance is longer, it requires more space between vehicles to allow for safe following distances [25].
Reaction Time $\xrightarrow{+}$ Reaction Distance	When a driver takes longer to react to a stimulus, the vehicle continues to move forward before the driver can begin to slow down or take other evasive actions [25].
Road Capacity $\xrightarrow{-}$ Density	When the road capacity is increased, it allows more vehicles to travel on the road without becoming congested, which can lead to lower traffic density [25].
Road Maintenance $\xrightarrow{-(\textit{with time lag})}$ Road Wear	When road maintenance activities are performed, road damages are repaired. The impact of road maintenance will lead to a reduction in wear and tear.
Road Maintenance $\xrightarrow{+}$ Number of Road Works	When road maintenance efforts are intensified, it results in more repair projects being undertaken [46].
Road Wear $\xrightarrow{-}$ Driver Comfort	As roads become more worn and degraded, the driving experience can become less comfortable due to factors such as uneven road surfaces, increased vibrations, and potential discomfort from road irregularities [45, 68].
Road Wear $\xrightarrow{+(\textit{with time lag})}$ Road Maintenance	As roads experience more wear and deterioration, it triggers a need for increased maintenance activities to address the damage. However, there might be a time delay before maintenance efforts are fully implemented [46].
Road Wear $\xrightarrow{+}$ Fuel Consumption	As road surfaces become more worn and degraded, vehicles may experience increased rolling resistance and potentially uneven surfaces. This can result in vehicles needing to exert more energy (and thus, more fuel) to maintain their speed [45, 46].
Road Wear $\xrightarrow{+}$ Noise level	As roads become more worn and degraded, the interaction between tires and the road surface can generate more noise, contributing to higher noise levels in the surrounding environment [45, 60].
Road Wear $\xrightarrow{+}$ Number of Accidents	As roads become more worn and degraded, they can contribute to deteriorated road surfaces, reduced traction, and potentially hazardous driving conditions. These adverse conditions can lead to an increase in the likelihood of accidents occurring [45].
Sensation Time $\xrightarrow{+}$ Mental Processing Time	When drivers take longer to sense a situation, it also takes them longer to mentally process the information, evaluate choices, and formulate an appropriate response [25, 37].
Situation Awareness Time $\xrightarrow{+}$ Mental Processing Time	When drivers take longer to understand a situation, it also takes them longer to mentally process the information, evaluate choices, and formulate an appropriate response [25, 37].
Speed $\xrightarrow{-}$ Travel Time	When a vehicle travels at a higher speed, it covers a distance in less time, resulting in a shorter travel time [22].
Speed $\xrightarrow{+}$ Air Drag	As the speed of a vehicle increases, the resistance generated by air drag also increases [25, 51].
Speed $\xrightarrow{+}$ Noise level	As vehicles travel at higher speeds, they generate more noise due to increased engine activity, tire-road interaction, and aerodynamic effects [59, 61].
Speed $\xrightarrow{+}$ Reaction Distance	When a vehicle is traveling at higher speeds, it covers more distance while the driver is reacting to a stimulus, compared to when the vehicle is traveling at lower speeds [25].
Speed $\xrightarrow{+}$ Traffic Flow	According to the fundamental diagram, an increase in traffic speed results in an increase of traffic flow (see Equation 3) [22].
Speed Homogeneity $\xrightarrow{-}$ Number Acceleration and Deceleration Maneuvers	When vehicles are moving at more consistent speeds, there is less need for changes in acceleration or deceleration [31].
Speed Homogeneity $\xrightarrow{-}$ Strength of Acceleration and Deceleration Maneuvers	When vehicles are moving at more consistent speeds, there is less need for extreme or abrupt changes in acceleration or deceleration [25, 32].
Speed Homogeneity $\xrightarrow{-}$ Number of Lane Changes	When vehicles are moving at more consistent speeds, there is less need for drivers to change lanes frequently to avoid slower-moving vehicles or to find gaps in traffic [62].
Speed Limit $\xrightarrow{+}$ Desired Speed	When the legal speed limit is higher, drivers may feel more inclined to travel at a faster pace, as they perceive they have more leeway to do so without breaking the law [25].
Strength of Acceleration and Deceleration Maneuvers $\xrightarrow{-}$ Speed Homogeneity	Stronger acceleration and deceleration maneuvers due to high speed variation lead to a decrease in speed homogeneity [25, 32].
Strength of Acceleration and Deceleration Maneuvers $\xrightarrow{-}$ Driver Comfort	When drivers perform more aggressive acceleration and deceleration maneuvers, it can lead to discomfort and a less pleasant driving experience [65–67].
Strength of Acceleration and Deceleration Maneuvers $\xrightarrow{+}$ Fuel Consumption	When drivers perform aggressive maneuvers that require frequent and rapid changes in speed, it can result in more fuel being consumed to power the vehicle [25].

Table 1 (continued)

Cause-effect relation	Evidence discussed
Structural Adaption of the Road Infrastructure $\xrightarrow{+}$ Cost of Habitat Damage	Increased structural adaptions of the road infrastructure contribute to increased habitat damage, which, results in various costs regarding habitat loss, fragmentation and degradation [70].
Structural Adaption of the Road Infrastructure $\xrightarrow{+}$ Number of Road Works	A need for road infrastructure adaptations results in an increase in road works.
Structural Adaption of the Road Infrastructure $\xrightarrow{+}$ Road Capacity	As road infrastructure is improved and expanded, it can result in higher road capacity, allowing more vehicles to travel on the road without excessive congestion [26–28].
Technical Response Time $\xrightarrow{+}$ Reaction Time	When a vehicle's response systems take longer to react to driver inputs or external events, it can lead to a delayed reaction time on the part of the driver [25].
Traffic Volume $\xrightarrow{+}$ Density	As more vehicles are added to the road, the density of vehicles within a given space increases [22].
Traffic Volume $\xrightarrow{+(\textit{with time lag})}$ Structural Adaption of the Road Infrastructure	As traffic volume increases over time, there is a subsequent need for road infrastructure to be adapted and expanded to accommodate the growing traffic demands [26–28].
Traffic Volume $\xrightarrow{+}$ Emissions	As traffic volume grows and more vehicles are on the road, there is an associated increase in the emissions generated by those vehicles [53].
Traffic Volume $\xrightarrow{+}$ Noise level	As traffic volume grows and more vehicles are on the road, the overall noise generated by vehicle engines, tires, and road interactions also increases [62].
Traffic Volume $\xrightarrow{+}$ Road Wear	As traffic volume grows and more vehicles travel on the road, it results in increased stress on the road surface and infrastructure, contributing to accelerated wear and deterioration [47].
Travel Time $\xrightarrow{+}$ Delay	As travel time grows longer, individuals experience more delays in reaching their destinations, often due to traffic congestion or unforeseen circumstances.
Vehicle Type Homogeneity $\xrightarrow{+}$ Speed Homogeneity	When there is greater uniformity in the types of vehicles on the road, it can contribute to smoother traffic flow and more consistent speeds among vehicles [33, 34].

Appendix D CLD-feedback loops

Table 2 Cause-Effect Loops

Loop	Cause-effect relation	Evidence discussed
B1	Traffic Volume $\xrightarrow{+}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Number of Alternative Routes taken $\xrightarrow{-}$ Traffic Volume	This feedback loop illustrates the complex relationship between traffic volume, density, speed, travel time, delay, and route choices. As traffic volume increases, it leads to congestion, slower speeds, and longer travel times and delays. Drivers may then choose alternative routes to avoid these delays. The decrease in traffic volume on the congested route improves traffic flow, speeds, travel times, and delays, making the initial route more attractive again [22, 26, 27].
B2	Traffic Volume $\xrightarrow{+}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Attractiveness of Public Transport $\xrightarrow{-}$ Traffic Volume	This feedback loop illustrates the complex interplay between traffic volume, density, speed, travel time, delay, and the attractiveness of public transport. As traffic volume increases, it can lead to congestion, slower speeds, longer travel times, and longer delays. If public transport becomes more appealing due to these factors, some commuters may shift to using public transport, which could lead to reduced traffic volume and congestion on the roads [22, 26–28].

Table 2 (continued)

Loop	Cause-effect relation	Evidence discussed
B3	Traffic Volume $\xrightarrow{+(\textit{with time lag})}$ Structural Adaptation of the Road Infrastructure $\xrightarrow{+}$ Number of Road Works $\xrightarrow{-}$ Road Capacity $\xrightarrow{-}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Number of alternative Routes taken $\xrightarrow{-}$ Traffic Volume	This feedback loop illustrates the interdependencies between traffic volume, road infrastructure adaptation and extension, road works, road capacity, density, speed, travel time, delays, and route choices. A steady increase in traffic volume may lead to a need in structural adaptations of the road infrastructure to cope with the increasing number of vehicles, which in turn causes temporary reductions in road capacity due to the needed road works. This, however, results in congestion, longer travel times, and longer delays, prompting drivers to seek alternative routes, temporarily reducing traffic volume [22, 25–28, 30].
B4	Traffic Volume $\xrightarrow{+(\textit{with time lag})}$ Structural Adaptation of the Road Infrastructure $\xrightarrow{+}$ Number of Road Works $\xrightarrow{-}$ Road Capacity $\xrightarrow{-}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Attractiveness of Public Transport $\xrightarrow{-}$ Traffic Volume	This feedback loop illustrates the interplay between traffic volume, road infrastructure adaptation and extension, road works, road capacity, density, speed, travel time, delay, and the attractiveness of public transport. A steady increase in traffic volume may lead to a need in structural adaptations of the road infrastructure to cope with the increasing number of vehicles, which in turn causes temporary reductions in road capacity due to the needed road works. This can result in congestion, longer travel times, and longer delays, prompting more drivers to switch to public transport, temporarily reducing traffic volume [22, 25–28, 30].
B5	Traffic Volume $\xrightarrow{+}$ Road Wear $\xrightarrow{+(\textit{with time lag})}$ Road Maintenance $\xrightarrow{+}$ Number of Road Works $\xrightarrow{-}$ Road Capacity $\xrightarrow{-}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Number of alternative Routes taken $\xrightarrow{-}$ Traffic Volume	This feedback loop highlights the interconnected nature of traffic volume, road wear, road maintenance, road works, road capacity, density, speed, travel time, delay, and route choices. An increase in traffic volume can contribute to road wear, leading to maintenance efforts and increased road works, which in turn causes temporary reductions in road capacity. This, however, results in congestion, longer travel times, and longer delays, prompting drivers to seek alternative routes, temporarily reducing traffic volume [22, 25–28, 30, 46, 47].
B6	Traffic Volume $\xrightarrow{+}$ Road Wear $\xrightarrow{+(\textit{with time lag})}$ Road Maintenance $\xrightarrow{+}$ Number of Road Works $\xrightarrow{-}$ Road Capacity $\xrightarrow{-}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Attractiveness of Public Transport $\xrightarrow{-}$ Traffic Volume	This feedback loop highlights the interconnected nature of traffic volume, road wear, road maintenance, road works, road capacity, density, speed, travel time, delay, and route choices. An increase in traffic volume can contribute to road wear, leading to maintenance efforts and increased road works, which in turn causes temporary reductions in road capacity. This can result in congestion, longer travel times, and longer delays, prompting more drivers to switch to public transport, temporarily reducing traffic volume [22, 25–28, 30, 46, 47].
B7	Road Wear $\xrightarrow{+(\textit{with time lag})}$ Road Maintenance $\xrightarrow{-(\textit{with time lag})}$ Road Wear	This feedback loop emphasizes the cyclical nature of road wear and maintenance. It showcases how maintenance efforts are activated in response to increasing road wear, which, in turn, leads to decreased road wear as the road surface is restored [46].

Table 2 (continued)

Loop	Cause-effect relation	Evidence discussed
B8	Traffic Volume $\xrightarrow{+}$ Road Wear $\xrightarrow{+}$ Number of Accidents $\xrightarrow{-}$ Road Capacity $\xrightarrow{-}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Number of alternative Routes taken $\xrightarrow{-}$ Traffic Volume	This feedback loop emphasises the interaction between traffic volume, road wear, accidents, road capacity, density, speed, travel time, delay and route choice. It shows how an increase in traffic can lead to road wear, which can then contribute to accidents, which in turn leads to a temporary reduction in road capacity. However, this leads to congestion, longer travel times, and longer delays, causing drivers to seek alternative routes, which temporarily reduces traffic [22, 25–28, 44, 45, 47].
B9	Traffic Volume $\xrightarrow{+}$ Road Wear $\xrightarrow{+}$ Number of Accidents $\xrightarrow{-}$ Road Capacity $\xrightarrow{-}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Attractiveness of Public Transport $\xrightarrow{-}$ Traffic Volume	This feedback loop emphasises the interaction between traffic volume, road wear, accidents, road capacity, density, speed, travel time, delay, and route choice. It shows how an increase in traffic can lead to road wear, which can then contribute to accidents, which in turn leads to a temporary reduction in road capacity. However, this leads to congestion, longer travel times, and longer delays, causing drivers to switch to public transport, which temporarily reduces traffic [22, 25–28, 44, 45, 47].
R1	Speed Homogeneity $\xrightarrow{-}$ Number of Acceleration and Deceleration Maneuvers $\xrightarrow{-}$ Speed Homogeneity	When speed homogeneity decreases, road users have to adapt their driving behaviour. More frequent braking and acceleration maneuvers are the necessary consequence in order to compensate for the speed variations in traffic and to avoid critical situations. However, the increased number of acceleration and deceleration maneuvers leads to a further increase in speed variation in the overall traffic, which in turn leads to a higher number of speed adjustments [31].
R2	Speed Homogeneity $\xrightarrow{-}$ Strength of Acceleration and Deceleration Maneuvers $\xrightarrow{-}$ Speed Homogeneity	When speed homogeneity decreases, road users have to adapt their driving behaviour. Stronger braking and acceleration maneuvers are the necessary consequence in order to compensate for the speed variations in traffic and to avoid critical situations. However, the increased maneuvering intensity leads to a further increase in speed variation in the overall traffic, which in turn leads to a higher number of speed adjustments [25, 32].
R3	Traffic Volume $\xrightarrow{+(\textit{with time lag})}$ Structural Adaption of the Road Infrastructure $\xrightarrow{+(\textit{with time lag})}$ Road Capacity $\xrightarrow{-}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Number of Alternative Routes taken $\xrightarrow{-}$ Traffic Volume	This feedback loop highlights how increases in traffic volume and attempted fixes in the form of infrastructure adaptations can fail with regard to traffic flow improvements. An initial increase in traffic volume leads to congestion and challenges the existing road infrastructure's capacity. As authorities respond by adapting the road infrastructure, road capacity increases, leading to reduced density, improved traffic flow as well as speeds, travel times and delays. Faster speeds, shorter travel times and less delays can make the route more attractive to drivers who would normally use alternative routes, attracting more drivers and increasing traffic even further [22, 25–28].

Table 2 (continued)

Loop	Cause-effect relation	Evidence discussed
R4	Road Capacity $\xrightarrow{-}$ Density $\xrightarrow{-}$ Speed $\xrightarrow{-}$ Travel Time $\xrightarrow{+}$ Delay $\xrightarrow{+(\textit{with time lag})}$ Attractiveness of Public Transport $\xrightarrow{-}$ Traffic Volume $\xrightarrow{+(\textit{with time lag})}$ Structural Adaption of the Road Infrastructure $\xrightarrow{+(\textit{with time lag})}$ Road Capacity	This feedback loop highlights how increases in traffic volume and attempted fixes in the form of infrastructure adaptations can fail with regard to traffic flow improvements. An initial increase in traffic volume leads to congestion and challenges the existing road infrastructure's capacity. As authorities respond by adapting the road infrastructure, road capacity increases, leading to reduced density, improved traffic flow as well as speeds, travel times and delays. Faster speeds, shorter travel times and less delays can make the route more attractive to road users who normally use public transport, attracting more drivers and increasing traffic volumes even further[22, 25–28].
R5	Density $\xrightarrow{+}$ Number of Stop and Go Movements $\xrightarrow{+}$ Number of Acceleration and Deceleration Maneuvers $\xrightarrow{-}$ Speed Homogeneity $\xrightarrow{-}$ Number of Lange Changes $\xrightarrow{+}$ Number of Accidents $\xrightarrow{-}$ Road Capacity $\xrightarrow{-}$ Density	This feedback loop illustrates how changes in traffic density by e.g. increasing traffic volumes can influence aspects of traffic behavior and safety. An increase in density can lead to more stop-and-go movements, acceleration and deceleration maneuvers, and disruptions in traffic flow. These disruptions result in decreased speed homogeneity and an increase in the number of lane changes, which raises the probability and number of accidents. Consequently, accidents reduce road capacity and lead to further increases in traffic density [25, 29–31, 42, 44, 62]

Author contributions

MW developed the system model in the form of the Causal Loop Diagram for this paper and made a substantial contribution to the preparation of the manuscript. MN provided ongoing support throughout the research and writing process and made a substantial contribution to the content of the article. Similarly, WS and AS made a substantial contribution to the manuscript through proofreading and feedback. All authors read and approved the final manuscript.

Funding

This article has been published open access with support of the TRA2024 project funded by the European Union. The work leading to the results in this paper was funded by the State of Upper Austria within the project SUBSTANTIATE (grant no. 895978), managed by the Austrian Research Promotion Agency (FFG). Furthermore, this research was supported by the project Intelligent Intersection (grant no. 880830), managed by the Austrian Research Promotion Agency (FFG).

Availability of data and materials

The dataset(s) supporting the conclusions of this article is (are) included within the article (and its additional file(s)).

Declarations

Competing interests

The authors declare that they have no known conflict of interest or personal relationships that could have appeared to influence the work reported in this paper.

Received: 2 October 2023 Accepted: 29 September 2024
Published online: 25 October 2024

References

1. Lu, N., Cheng, N., Zhang, N., Shen, X., & Mark, J. W. (2014). Connected vehicles: Solutions and challenges. *IEEE Internet of Things Journal, 1*(4), 289–299. https://doi.org/10.1109/JIOT.2014.2327587
2. Statista (2023). Number of connected cars in European countries in 2023 \| Statista (21/08/2023). https://statista.com/prognosen/893902/anzahl-an-vernetzten-fahrzeugen-laendervergleich-europa Accessed 21/08/2023.
3. EUROPEAN COMMISSION. A European strategy on Cooperative Intelligent Transport Systems, a milestone towards cooperative, connected and automated mobility, Brussels.
4. Eurostat (2023). Statistics \| Eurostat: Stock of vehicles by category and NUTS 2 regions. https://ec.europa.eu/eurostat/databrowser/view/tran_r_vehst/default/table?lang=en. Accessed 21/08/2023.
5. Ritchie, H., Roser, M., Rosado, P. (2020). Co_2 and greenhouse gas emissions. Our World in Data.
6. Decae, R. (2021). European Road Safety Observatory: Annual statistical report on road safety in the EU 2021.
7. El Beyrouty, K., Loehr, E., Nokes, T., Brannigan, C., Levin, S., Biedka, M., Figg, H., Asselin-Miller, N., Fermi, F., Fiorello, D., Loredana, Z., Skinner, I. Support study for Impact Assessment of Cooperative Intelligent Transport Systems.
8. DRIVE C2X-DRIVing implementation and Evaluation of C2X communication technology in Europe (21/08/2023). https://cordis.europa.eu/project/id/270410/de Accessed 21/08/2023.
9. Compass4D - Cooperative Mobility Pilot on Safety and Sustainability Services for Deployment (21/08/2023). https://cordis.europa.eu/project/id/325179 Accessed 21/08/2023.
10. FOTsis Project - European Field Operational Test on Safe, Intelligent and Sustainable Road Operation (21/08/2023). https://cordis.europa.eu/project/id/270447 Accessed 21/08/2023.
11. InterCor-Interoperable Corridors Deploying Cooperative Intelligent Transport Systems (02/09/2022). https://intercor-project.eu/ Accessed 02/09/2022.
12. NordicWay 3 (21/08/2023). https://www.nordicway.net/ Accessed 21/08/2023.

13. C-Roads (21/08/2023). www.c-roads.eu/platform.html Accessed 21/08/2023.
14. Car-2-Car Communication Consortium (21/08/2023). https://www.car-2-car.org/index.php?id=1 Accessed 21/08/2023.
15. European Parliament: Directive 2010/40/EU of the European Parliament and of the Council of 7 July 2010 on the framework for the deployment of Intelligent Transport Systems in the field of road transport and for interfaces with other modes of transport, 2018.
16. Hayes, Adrian C.. (2017). What is impact assessment? Some personal reflections C. P. Wolf (1933–2015), edited posthumously by Adrian C. Hayes. *Impact Assessment and Project Appraisal, 35*(3), 186–199. https://doi.org/10.1080/14615517.2017.1322812
17. Walch, M., Schirrer, A., & Neubauer, M. (2024). Impact assessment of cooperative intelligent transport systems (C-ITS)–a structured literature review. submitted to: European Transport Research Review; current status: accepted with revisions.
18. Innamaa, Satu, Smith, Scott, Wilmink, Isabel, & Reed, Nick. (2018). Impact Assessment. In Gereon Meyer & Sven Beiker (Eds.), *Road Vehicle Automation 4* (pp. 45–55). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-60934-8_5
19. Rakoff, H.E., Smith, S., Innamaa, S., Barnard, Y., Harrison, G., & Shaw, J. (2020). Building feedback into modelling impacts of automated vehicles: Developing a consensus model and quantitative tool. In: Lusikka, T. (ed.) *Proceedings of TRA2020, the 8th Transport Research Arena*, pp. 109–110. https://eprints.whiterose.ac.uk/154905/.
20. Sterman, J.D. (2000). Business dynamics, system thinking and modeling for a complex world vol. 19. https://www.researchgate.net/publication/44827001_Business_Dynamics_System_Thinking_and_Modeling_for_a_Complex_World.
21. Hördur V. Haraldsson (2001). Introduction to systems and causal loop diagrams adapted.
22. Knoop, V.L. (2018). Introduction to traffic flow theory: An introduction with exercises.
23. Greenshields, B., Bibbins, J., Channing, W. S., & Miller, H. (1935). A study of traffic capacity. *Proceedings of the Highway Research Board, 14*, 448–477.
24. Drake, J. L., & Joseph L. Schofer, A. D. (1966). May: A statistical analysis of speed-density hypotheses. *Highway Research Record, 154*, 53–87.
25. Treiber, M., & Kesting, A. (2013). *Traffic Flow Dynamics: Data. Models and Simulation*. Heidelberg and New York: Springer.
26. Mogridge, M. J. H. (1997). The self-defeating nature of urban road capacity policy. *Transport Policy, 4*(1), 5–23. https://doi.org/10.1016/S0967-070X(96)00030-3
27. Goodwin, P. (1997). Doomsday postponed. *Transport Policy, 4*(1), 1–3. https://doi.org/10.1016/S0967-070X(97)84797-X
28. Kane, L., Behrens, R. (2000). The traffic impacts of road capacity change: a review of recent evidence and policy debates.
29. Yeo, H., & Skabardonis, A. (2009). Understanding stop-and-go traffic in view of asymmetric traffic theory. In: Lam, W.H.K., Wong, S.C., Lo, H.K. (eds.) *Transportation and Traffic Theory 2009*, pp. 99–115. Springer, Dordrecht. https://doi.org/10.1007/978-1-4419-0820-9.
30. Suh, J., & Yeo, H. (2016). An empirical study on the traffic state evolution and stop-and-go traffic development on freeways. *Transportmetrica A Transport Science, 12*(1), 80–97. https://doi.org/10.1080/23249935.2015.1101508
31. Goñi Ros, B., Knoop, V. L., Arem, B., & Hoogendoorn, S. P. (2014). Empirical analysis of the causes of stop-and-go waves at sags. *IET Intelligent Transport Systems, 8*(5), 499–506. https://doi.org/10.1049/iet-its.2013.0102
32. Wiedemann, R. (1974). *Simulation des Straßenverkehrsflusses: Schriftenreihe des Instituts Für Verkehrswesen der Universität Karlsruhe*. Germany: Karlsruhe.
33. Moridpour, S., Mazloumi, E., & Mesbah, M. (2015). Impact of heavy vehicles on surrounding traffic characteristics. *Journal of Advanced Transportation, 49*(4), 535–552. https://doi.org/10.1002/atr.1286
34. Vlahogianni, E. I. (2007). Some empirical relations between travel speed, traffic volume and traffic composition in urban arterials. *IATSS Research, 31*(1), 110–119. https://doi.org/10.1016/S0386-1112(14)60189-8
35. Kesting, A., & Treiber, M. (2008). How reaction time, update time, and adaptation time influence the stability of traffic flow. *Computer-Aided Civil and Infrastructure Engineering, 23*(2), 125–137. https://doi.org/10.1111/j.1467-8667.2007.00529.x
36. Kesting, A., & Treiber, M. (2006). Influence of reaction times and anticipation on the stability of vehicular traffic flow. *IFAC Proceedings Volumes, 39*(10), 205–210. https://doi.org/10.3182/20060710-3-IT-4901.00034
37. Shiffrin, R. M., & Schneider, W. (1977). Controlled and automatic human information processing: Ii. perceptual learning, automatic attending and a general theory. *Psychological Review, 84*(2), 127–190. https://doi.org/10.1037/0033-295X.84.2.127
38. El-Shawarby, Ihab, Abdel-Salam, Abdel-Salam G.., & Rakha, Hesham. (2013). Evaluation of driver perception–reaction time under rainy or wet roadway conditions at onset of yellow indication. *Transportation Research Record: Journal of the Transportation Research Board, 2384*(1), 18–24. https://doi.org/10.3141/2384-03
39. Pisano, P., Goodwin, L.C.: Surface transportation weather applications. In: *ITE 2002 Annual Meeting and Exhibit*, pp. 1–11. ITE, Washington DC/USA (2002). https://trid.trb.org/view/732438
40. Ting, P.-H., Hwang, J.-R., Doong, J.-L., & Jeng, M.-C. (2008). Driver fatigue and highway driving: a simulator study. *Physiology & Behavior, 94*(3), 448–453. https://doi.org/10.1016/j.physbeh.2008.02.015
41. Otmani, S., Pebayle, T., Roge, J., & Muzet, A. (2005). Effect of driving duration and partial sleep deprivation on subsequent alertness and performance of car drivers. *Physiology & Behavior, 84*(5), 715–724. https://doi.org/10.1016/j.physbeh.2005.02.021
42. Allex, B., & Ortner, S. 2021. Straßenverkehrsunfälle, Vienna.
43. Abegaz, Teferi, Berhane, Yemane, Worku, Alemayehu, Assrat, Abebe, & Assefa, Abebayehu. (2014). Effects of excessive speeding and falling asleep while driving on crash injury severity in Ethiopia: A generalized ordered logit model analysis. *Accident Analysis & Prevention, 71*, 15–21. https://doi.org/10.1016/j.aap.2014.05.003
44. Chin, S.-M., Franzese, O., Greene, D.L., Hwang, H.L., & Gibson, R. (2004). Temporary Losses of Highway Capacity and Impacts on Performance: Phase 2. https://rosap.ntl.bts.gov/view/dot/37083
45. Ihs, A., Magnusson, G.: The significance of various road surface properties for traffic and surroundings. http://vti.diva-portal.org/smash/record.jsf?pid=diva2.
46. Lepert, P., & Brillet, F. (2009). The overall effects of road works on global warming gas emissions. *Transportation Research Part D: Transport and Environment, 14*(8), 576–584. https://doi.org/10.1016/j.trd.2009.08.002
47. Nilsson, J.-E., Svensson, K., & Haraldsson, M. (2020). Estimating the marginal costs of road wear. *Transportation Research Part A: Policy and Practice, 139*, 455–471. https://doi.org/10.1016/j.tra.2020.07.013
48. Pais, J. C., Amorim, S. I. R., & Minhoto, M. J. C. (2013). Impact of traffic overload on road pavement performance. *Journal of Transportation Engineering, 139*(9), 873–879. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000571
49. Schirrer, Alexander, Gratzer, Alexander L.., Thormann, Sebastian, Jakubek, Stefan, Neubauer, Matthias, & Schildorfer, Wolfgang (Eds.). (2022). *Energy-Efficient and Semi-automated Truck Platooning: Research and Evaluation*. Cham: Springer International Publishing.
50. Duan, K., McDaniel, C., Muller, A., Yokota, B.: Effects of Highway Slipstreaming on California Gas Consumption. https://www.semanticscholar.org/paper/Effects-of-Highway-Slipstreaming-on-California-Gas-Duan-McDaniel/72fa130a18b006b42bd777f2acca6b6f88ea3abc.
51. Kallenbach, S. (2019). Truck platooning–a pragmatical approach. In T. Bertram (Ed.), *Fahrerassistenzsysteme 2018* (pp. 132–157). Wiesbaden: Springer Fachmedien Wiesbaden.
52. Greene, S., & Lewis, A. Global Logistics Emissions Council Framework for Logistics Emissions Accounting and Reporting: version 2.0, Amsterdam.
53. Ajayi, S. A., Adams, C. A., Dumedah, G., Adebanji, A. O., & Ackaah, W. (2023). The impact of traffic mobility measures on vehicle emissions for heterogeneous traffic in lagos city. *Scientific African, 21*, 01822. https://doi.org/10.1016/j.sciaf.2023.e01822
54. Khreis, Haneen, Warsow, Karyn M.., Verlinghieri, Ersilia, Guzman, Alvaro, Pellecuer, Luc, Ferreira, Antonio, Jones, Ian, Heinen, Eva, Rojas-Rueda, David, Mueller, Natalie, Schepers, Paul, Lucas, Karen, & Nieuwenhuijsen, Mark. (2016). The health impacts of traffic-related exposures in urban areas: Understanding real effects, underlying driving forces and co-producing future directions. *Journal of Transport & Health, 3*(3), 249–267. https://doi.org/10.1016/j.jth.2016.07.002
55. Künzli, N., Kaiser, R., Médina, S., Studnicka, M., Chanel, O., Filliger, P., Herry, M., Horak, F., Puybonnieux-Texier, V., Quénel, P., Schneider, J., Seethaler, R., Vergnaud, J., & Sommer, H. (2000). Public-health impact of outdoor and

traffic-related air pollution: A European assessment. *The Lancet, 356*(9232), 795–801. https://doi.org/10.1016/S0140-6736(00)02653-2
56. Wang, D., Liu, Q., Ma, L., Zhang, Y., & Cong, H. (2019). Road traffic accident severity analysis: A census-based study in China. *Journal of Safety Research, 70*, 135–147. https://doi.org/10.1016/j.jsr.2019.06.002
57. Richter, M., Krettek, C., Otte, D., Wiese, B., Stalp, M., Ernst, S., & Pape, H. C. (2001). Correlation between crash severity, injury severity, and clinical course in car occupants with thoracic trauma: a technical and medical study. *The Journal of Trauma, 51*(1), 10–16. https://doi.org/10.1097/00005373-200107000-00002
58. Brown, A. L. (2015). Effects of road traffic noise on health: From burden of disease to effectiveness of interventions. *Procedia Environmental Sciences, 30*, 3–9. https://doi.org/10.1016/j.proenv.2015.10.001
59. Peng, J., Parnell, J., & Kessissoglou, N. (2019). A six-category heavy vehicle noise emission model in free-flowing condition. *Applied Acoustics, 143*, 211–221. https://doi.org/10.1016/j.apacoust.2018.08.030
60. Berge, T., Mioduszewski, P., Ejsmont, J., & Swieczko-Zurek, B. (2017). Reduction of road traffic noise by source measures–present and future strategies. *Noise Control Engineering Journal, 65*(6), 549–559. https://doi.org/10.3397/1/376568
61. V. Desarnaulds, G. Monay, A. Carvalho (2004). Noise reduction by urban traffic management. In: *Proceedings of the 18th International Congress on Acoustics*. https://www.semanticscholar.org/paper/Noise-reduction-by-urban-traffic-management-Desarnaulds-Monay/5811fb163323a8e87374b834ba256ea59167067b
62. Kamandang, Zetta Rasullia, Wibisana, Hendrata, & Casita, Cintantya Budi. (2020). Analysis of noise pollution due to traffic volume based on the types of automotive vehicles: A study of west surabaya region. *Journal of Physics: Conference Series, 1569*(4), 042044. https://doi.org/10.1088/1742-6596/1569/4/042044
63. Rochat, Judith L., & Reherman, Clay N. (2005). Federal highway administration (FHWA) Roadway construction noise model (RCNM). *The Journal of the Acoustical Society of America, 118*, 1954. https://doi.org/10.1121/1.4781362
64. Kühne, J., Edwards, G.: Strategic Roads User Survey: Analysis of key drivers of overall satisfaction.
65. Li, Z., Fu, R., Wang, C., & Stoffregen, T. A. (2020). Effects of linear acceleration on passenger comfort during physical driving on an urban road. *International Journal of Civil Engineering, 18*(1), 1–8. https://doi.org/10.1007/s40999-019-00473-8
66. Winkel, K. N., Irmak, T., Happee, R., & Shyrokau, B. (2023). Standards for passenger comfort in automated vehicles: Acceleration and jerk. *Applied Ergonomics, 106*, 103881. https://doi.org/10.1016/j.apergo.2022.103881
67. Qin, Y., Wang, H., & Ran, B. (2019). Impact of connected and automated vehicles on passenger comfort of traffic flow with vehicle-to-vehicle communications. *KSCE Journal of Civil Engineering, 23*(2), 821–832. https://doi.org/10.1007/s12205-018-1990-6
68. Ihs, A.: The influence of road surface condition on traffic safety and ride comfort. VTI Särtryck, 11–21 (2005)
69. Ramdas, V.: Highway service levels. TRL Ltd, Wokingham
70. van Essen, H., van Wijngaarden, L., Schroten, A., Sutter, D., Bieler, C., Maffii, S., Brambilla, M., Fiorello, D., Fermi, F., Parolin, R., El Beyrouty, K.: *Handbook on the external costs of transport*. Publications Office. https://doi.org/10.2832/51388
71. ESRIUM: ESRIUM - Safe and efficient roads (25.01.2022). https://esrium.eu/ Accessed 17.08.2023
72. Harvas, G., Schildorfer, W., Hofbauer, F., Walch, M., Neubauer, M.: ESRIUM Deliverable 2.1 Use Case Definition. https://esrium.eu/wp-content/uploads/2021/07/ESRIUM_DEL_NNG_2021-07-01_WP2_D2.1-Use-Cases_v1.pdf
73. Ognissanto, F., Hopkin, J., & Stevens, A. (2019). Investigation of the costs, benefits and funding models for two bundles of cooperative intelligent transport system services. *IET Intelligent Transport Systems, 13*(6), 1048–1056. https://doi.org/10.1049/iet-its.2018.5399
74. Car 2 Car Communication Consortium: Guidance for day 2 and beyond roadmap (21/08/2023). https://www.car-2-car.org/fileadmin/documents/General_Documents/C2CCC_WP_2072_RoadmapDay2AndBeyond.pdf Accessed 21/08/2023.
75. ETSI: ETSI TS 102 638 V1.1.1 (2009-06): Intelligent Transport Systems (ITS); Vehicular Communications; Basic Set of Applications; Definitions (06/2009)
76. C-Roads: Implemented Services (21/08/2023). https://www.c-roads.eu/pilots/implemented-services.html Accessed 21/08/2023
77. Rämä, P., & Innamaa, S. (2020). Safety assessment of local cooperative warnings and speed limit information. *IET Intelligent Transport Systems, 14*(13), 1769–1777. https://doi.org/10.1049/iet-its.2019.0668
78. Farah, H., Koutsopoulos, H. N., Saifuzzaman, M., Kölbl, R., Fuchs, S., & Bankosegger, D. (2012). Evaluation of the effect of cooperative infrastructure-to-vehicle systems on driver behavior. *Transportation Research Part C: Emerging Technologies, 21*(1), 42–56. https://doi.org/10.1016/j.trc.2011.08.006

Publisher's Note